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**Simulation of Pressure and Temperature
Responses for the 20 Inch Supersonic
Wind Tunnel**

Mark A. Motter

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Abstract

A simulation of the pressure and temperature responses of the 20 Inch Supersonic Wind Tunnel (SWT) is developed. The simulation models the tunnel system as a set of lumped-parameter volumes connected by flow regulating elements such as valves and nozzles. Simulated transient responses of temperature and pressure for the five boundary points of the 20 Inch Supersonic Wind Tunnel operating map are produced from their respective initial conditions, tunnel operating conditions, heater input power, and valve positions. Upon reaching steady state, a linearized model for each operating point is determined. Both simulated and actual tunnel responses are presented for comparison.

Nomenclature

| | |
|------------------------|---|
| <i>A</i> | area |
| <i>D</i> | diameter |
| <i>E</i> | energy |
| <i>k</i> | thermal conductivity |
| <i>m</i> | mass |
| MW | megawatts |
| <i>P</i> | pressure |
| <i>Q</i> | heat |
| <i>JTC</i> | Joule-Thompson coefficient |
| <i>Re</i> | Reynolds number |
| <i>Pr</i> | Prandtl number |
| <i>T</i> | temperature |
| <i>v</i> | volume |
| <i>V</i> | voltage |
| <i>w</i> | thermal mass |
| <i>W</i> | flow |
| <i>C</i> | flow coefficient |
| <i>R</i> | resistance |
| <i>c_p</i> | constant pressure specific heat (0.241 Btu/lbm- R) |
| <i>c_v</i> | constant volume specific heat (0.171 Btu/lbm- R) |
| γ | c_p/c_v (1.4) |
| <i>R</i> | gas constant (53.3 ft-lbf/lb- R) |
| <i>g</i> | acceleration due to gravity (32.2 ft/sec ^{**2}) |
| <i>T_{ref}</i> | reference temperature (460 R) |

Subscripts:

| | |
|-----------|--------------------|
| <i>cv</i> | control volume |
| <i>i</i> | inlet |
| <i>o</i> | outlet |
| <i>m</i> | surrounding vessel |

1.0 Introduction

A simulation which models the pressure and temperature responses of the 20 Inch Supersonic Wind Tunnel (SWT) has been developed. This simulation is intended to provide a basis for developing pressure and temperature control laws for the 20 Inch SWT.

The simulation is written in the Advanced Continuous Simulation Language (ACSL). ACSL provides the capability to simulate the response of systems represented by nonlinear, time-varying differential

equations. Transient responses are simulated by supplying an appropriate set of initial conditions and time history of inputs. Run-time commands are invoked during the simulation execution to determine a linearized system model based on small perturbations about desired operating points. Eigenvalues of the linearized system are then determined for those particular operating conditions.

The major elements which comprise the tunnel system are shown in Figure 1. Six volumes, each describing a section of the tunnel system, represent the 20 Inch SWT:

- Bottlefield
- Heate Upstream
- Heater Downstream
- Mixing Tee
- Settling Chamber
- Vacuum Spheres

Flow between these volumes is calculated at seven points:

- Valve 3162
- Heater
- Valve 3295
- Valve 3170
- Valve 3292
- Valve 3296
- Nozzle

Mass and energy are balanced for each volume. The rate of mass transfer is simulated by calculating the entering and exiting flow rates. The mass of air within a volume is determined by integrating the net rate of mass transfer. The rate of energy exchange is simulated by calculating the enthalpy of the entering and exiting air flows as well as the heat transfer to the surrounding vessel. Similarly, the energy of the air within a volume is determined by integrating the net rate of energy exchange. Consequently, the temperature of the air within a volume is determined from the ratio of energy to mass. The pressure is determined from the ideal gas equation of state.

Each volume and flow calculation is explicitly identified in the simulation source code. Pertinent parameters used to model each system element are shown in Figure 1. Inputs to the simulation are: initial conditions for temperature and pressure, valve positions, and heater input power. Alternately, heater input power may be specified by the tap position of a variable autotransformer. Outputs from the simulation are the temperature and pressure responses of each volume.

The settling chamber, nozzle, and valve 3296 are the simulation elements specific to the 20 Inch SWT. The remaining simulation elements are common to other test cells that use the Mach 8 Air Distribution System. Responses for the other test cells may be simulated by inserting equations to represent the specific test cell elements between the mixing tee and the vacuum spheres. Operating conditions that discharge to the atmosphere instead of to the vacuum spheres are also accommodated.

2.0 Governing Equations

Equations describing the fundamental relationships between the system elements shown in Figure 1 are based on mathematical models appropriate to the type of system element. Modeling techniques used for the general types of elements are: First Law control volume analysis for volumes, manufacturer's published flow equations for valves, and idealized flow characteristics for the heater and nozzle orifices.

2.1 Volume Models

For each of the volumes used to represent the 20 Inch SWT, a mass and energy balance is performed. The temperature and pressure are determined directly from the mass and energy within the volume.

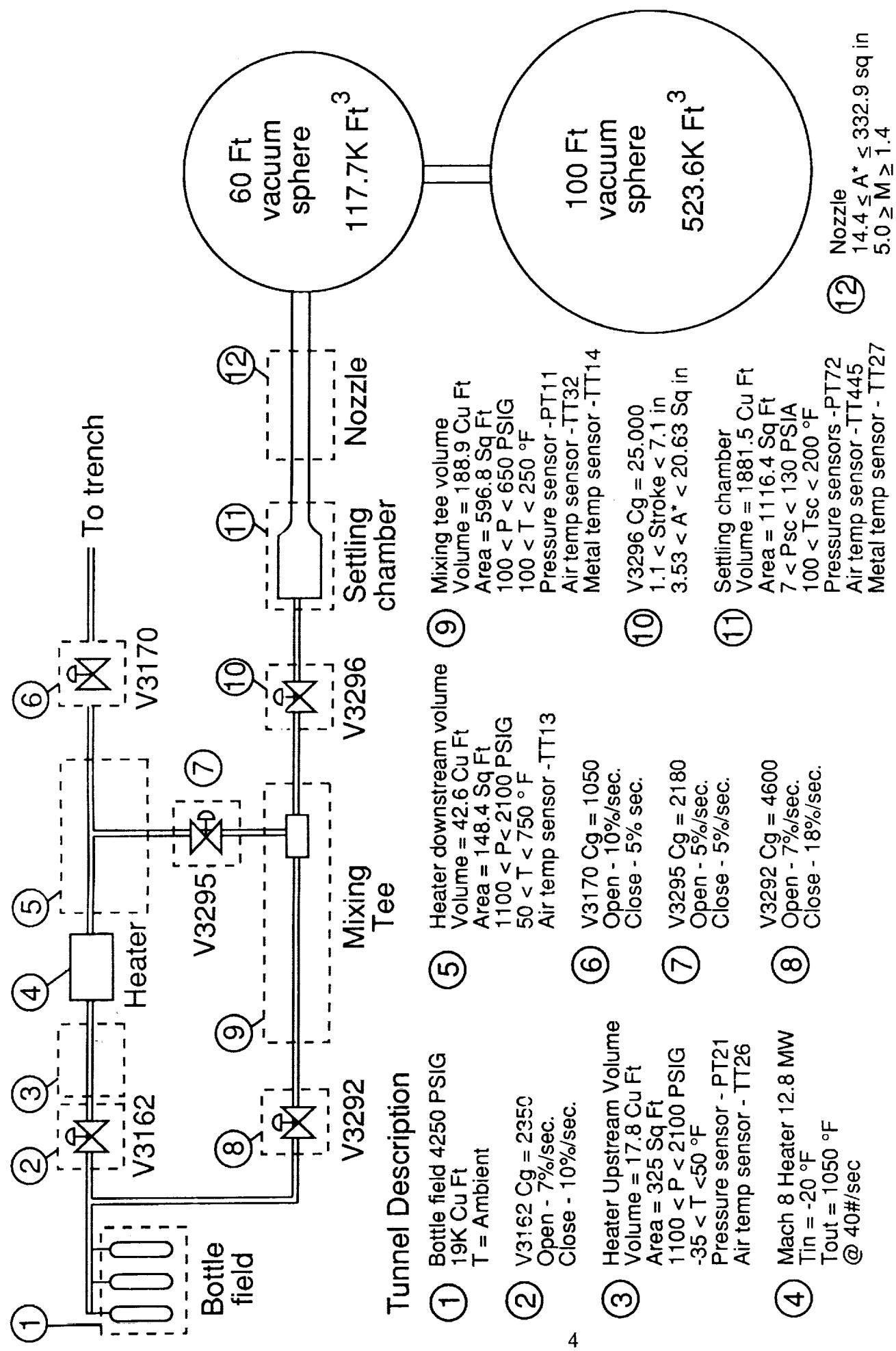


Figure 1. System Diagram

Heat transfer to and from the surrounding vessel is considered to be by forced convection only. The vessel is assumed to be perfectly insulated. Figure 2 shows the representation of a typical volume.

Mass Balance.

$$\dot{m}_{cv} = \dot{m}_i - \dot{m}_o \quad (1)$$

$$m_{cv} = \int \dot{m}_{cv} + m_{ic} \quad (2)$$

$$m_{ic} = P_{ic}v/(RT_{ic}) \quad (3)$$

Energy Balance.

$$\dot{E}_{cv} = c_p (\dot{m}_i T_i - \dot{m}_o T_o) - \dot{Q}_m \quad (4)$$

$$E_{cv} = \int \dot{E}_{cv} + E_{ic} \quad (5)$$

$$E_{ic} = m_{ic} c_v (T_{ic} - T_{ref}) \quad (6)$$

Temperature.

Temperature is determined from the internal energy and the mass within the volume:

$$T_{cv} = E_{cv}/(c_v m_{cv}) + T_{ref} \quad (7)$$

Pressure.

Pressure is determined using the Ideal gas equation:

$$P_{cv} = \frac{m_{cv} T_{cv} R}{v} \quad (8)$$

Heat Transfer.

Heat transfer to the surrounding vessel is based on flow through a round duct:

$$\dot{Q}_m = U \cdot A \cdot (T_{cv} - T_m) \quad (9)$$

where

$$U = .023 \frac{k}{D} (Re)^{0.8} (Pr)^{0.4} \quad (10)$$

Metal Temperature.

The temperature of the surrounding vessel is determined by integrating the rate of heat flow into the respective thermal mass:

$$T_m = \frac{1}{w_m} \int \dot{Q}_m + T_{mic} \quad (11)$$

2.2 Flow Models

Valves.

The flow through valves V3162, V3170, V3292, V3295, and V3296 is modeled using a published flow equation from Fisher Controls [4]:

$$W = K_v \delta C_v P_H / \sqrt{T_H} \quad (12)$$

where

$$K_v = 4.84 \times 10^{-4}$$

δ - valve stroke

P_H - upstream pressure

T_H - upstream temperature

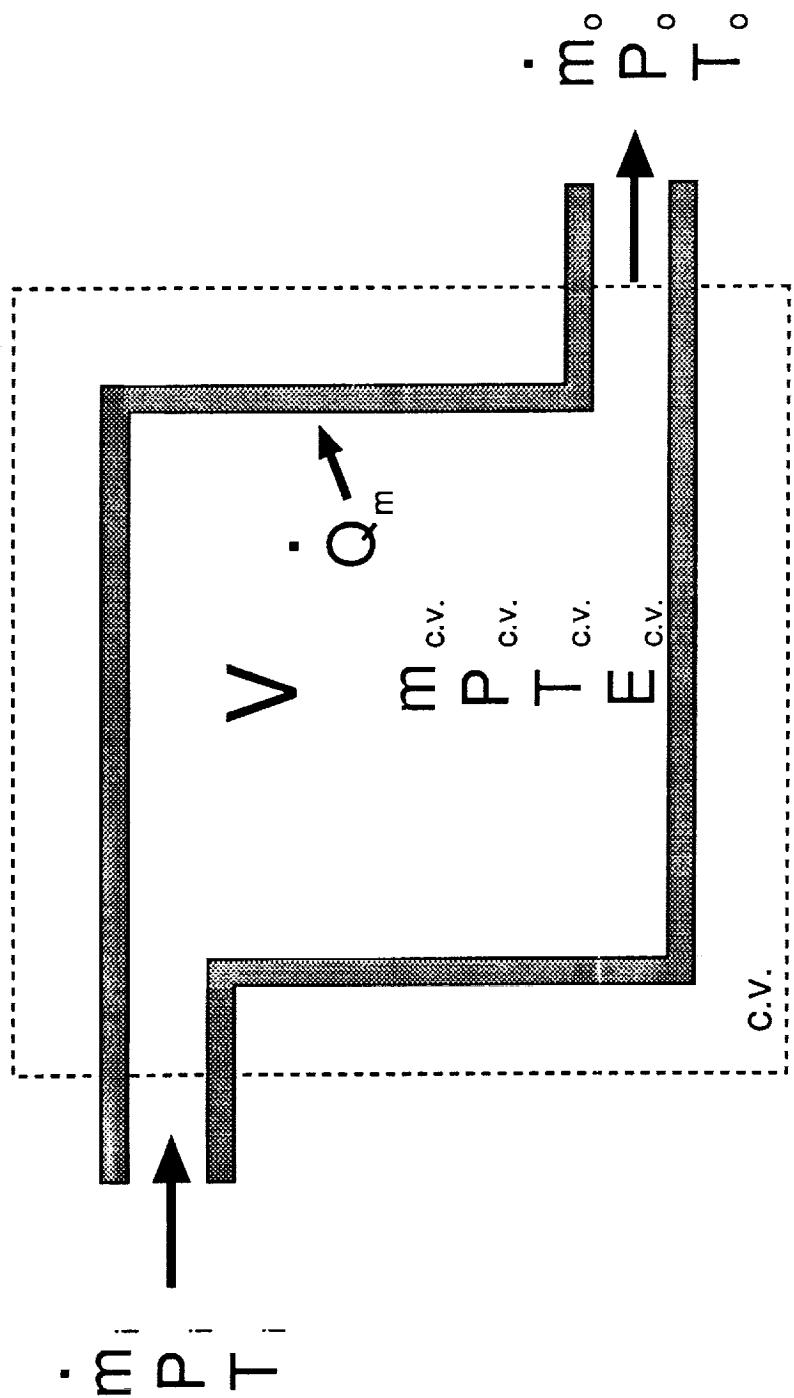


Figure 2. Typical volume

$$C_v = C_G(\delta) \sin \left[\frac{59.54}{C_1} \sqrt{1 - \frac{P_L}{P_H}} \right]$$

where

$C_G(\delta)$ - flow factor based on valve stroke δ

C_1 - flow recovery factor from manufacturer's data

P_L - downstream pressure

Heater.

Flow through the heater is modeled by:

$$W = \sqrt{C_v P_H (P_H - P_L) / T_H} \quad (13)$$

where

$C_v = 25.17$ for M8 Heater

P_H upstream pressure

P_L downstream pressure

T_H upstream temperature

Nozzle.

The nozzle flow is determined by:

$$W = AP_H \left(\frac{P_L}{P_H} \right)^{1/\gamma} \sqrt{\frac{2g\gamma}{(\gamma - 1)RT_H} \left[1 - \left(\frac{P_L}{P_H} \right)^{\frac{\gamma-1}{\gamma}} \right]} \quad (14)$$

when

$$\frac{P_L}{P_H} \leq 0.5283$$

and

$$W = AP_H \sqrt{\frac{g\gamma}{RT_H} \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)}} \quad (15)$$

when

$$\frac{P_L}{P_H} > 0.5283$$

where A - nozzle cross-sectional area

2.3 Heater Model

The heat input to the system by the Mach 8 Heater is determined from the electrical power input :

$$\text{HPOWER} = V_{TAP}^2 / R_{HTR} \quad (16)$$

where

$$V_{TAP} = f(\text{TAP POSITION}) \quad (17)$$

and

$$R_{HTR} = R_{k0} + R_{k1}(T_{HTR} - 615) \quad (18)$$

The thermal equivalent of the electrical input power is transferred into the Heater Downstream volume through the thermal mass of the heater core. This provides a simulation of heater core temperature

dependent on heater mass flow rate, heater input power, and heater outlet temperature. The electrical power input may be specified directly in MW or by the autotransformer tap position.

2.4 Throttling Process

The temperature drop associated with throttling across valves is determined using the Joule-Thompson coefficient and the associated pressure drop:

$$\Delta T = JTC \cdot (P_H - P_L) \quad (19)$$

3.0 Method of Solution

A computer model of the above equations was implemented using ACSL (Appendix B). ACSL provides a simple method of representing the mathematical equations on a digital computer. ACSL sorts the continuous model equations, in contrast to programming languages such as FORTRAN where program execution depends critically on statement order. The nonlinear, time dependent differential equations are solved directly by integrating from a given set of initial conditions to a final state determined by system inputs. The state variables for the 20 Inch SWT model are listed in Table 1.

Table 1. State Variables

| <u>State Variable</u> | <u>ACSL Variable Name</u> |
|-------------------------------------|---------------------------|
| Bottlefield Energy | BFENRG |
| Bottlefield Mass | BFMAS |
| Heater Upstream Energy | HUENRG |
| Heater Upstream Mass | HUMAS |
| Heater Upstream Metal Temperature | HUTPIP |
| Heater Downstream Energy | HDENRG |
| Heater Downstream Mass | HDMAS |
| Heater Downstream Metal Temperature | HDTPIP |
| Heater Core Temperature | TCORER |
| Mixing Tee Energy | MTENRG |
| Mixing Tee Mass | MTMAS |
| Mixing Tee Metal Temperature | MTTPIP |
| Piping Energy | PPENRG |
| Piping Metal Temperature | PPTPIP |
| Settling Chamber Energy | SCENRG |
| Settling Chamber Mass | SCMAS |
| Settling Chamber Metal Temperature | SCTPIP |
| Vacuum Sphere Energy | VSENRG |
| Vacuum Sphere Mass | VSMAS |

4.0 Results

The model was exercised for the five boundary points that establish the 20 Inch SWT operating map shown in Figure 3. The simulation was driven by values of valve positions and heater power read directly from files of data logged during actual tunnel runs. Initial mass and energy states for each volume were determined from pressure and temperature conditions at the beginning of the run. Initial

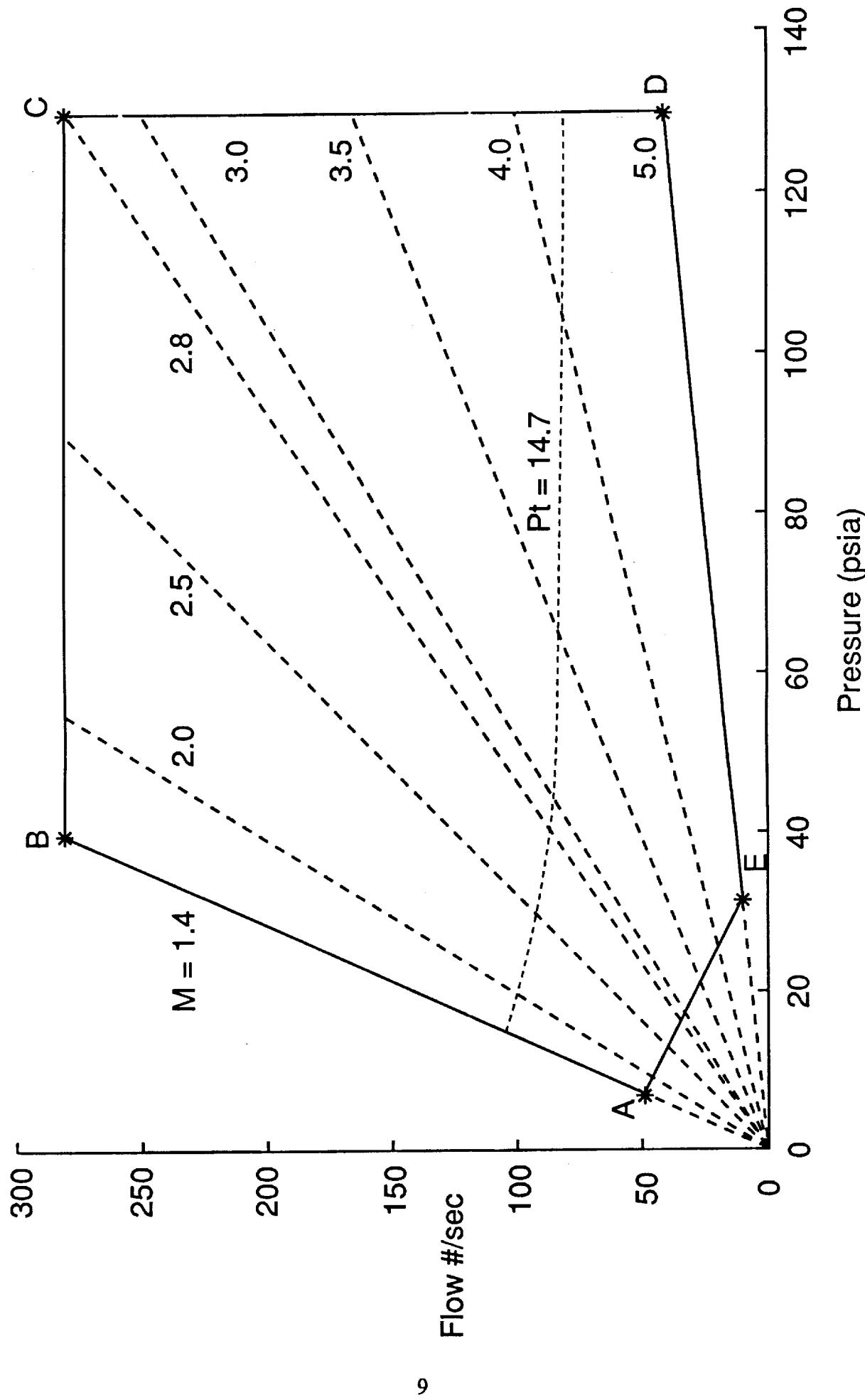


Figure 3. 20 Inch SWT Operating Map

values for piping and pressure vessel temperatures were set according to either the available sensor readings or the assumption of thermal equilibrium within the volume.

Figure 4 shows the results of a simulation run at operating condition 'A'. The first plot compares the simulated settling chamber pressure to the actual pressure logged during a tunnel run. The second plot similarly compares the simulated and actual settling chamber temperatures. The third plot shows the actual valve positions logged during the tunnel run. These valve positions were used as part of the dynamic input to the simulation. Similarly, the last plot shows the actual heater power logged during the run. This data was also used as dynamic input to the simulation. Thus, the simulation output, in terms of settling chamber pressure and temperature, may be compared to the actual tunnel response for an identical set of inputs. The position commands to valves V3295 and V3292 were specified by a human operator during the tunnel run. Similarly, the heater electrical power was controlled manually by selecting the autotransformer tap position during the run.

Referring to Figure 3, operating point 'A' is characterized by a settling chamber absolute pressure of seven pounds per square inch, corresponding to a mass flow rate of fifty pounds per second. The desired settling chamber temperature is 100 degrees Fahrenheit. A complete listing of operating point parameters is provided in Appendix A.

Figure 5 shows the same data for a simulation of operating condition 'B'. Point 'B' is characterized by a settling chamber absolute pressure of 40 pounds per square inch, corresponding to a mass flow rate of 280 pounds per second. The desired settling chamber temperature is 100 degrees Fahrenheit.

Figures 6-8 provide a more comprehensive view of the simulation capability. These figures show the results of a run at operating point 'C'. Figure 6 shows the same results as for points 'A' and 'B'. Figure 7 shows the simulated and actual tunnel responses for heater outlet air temperature, mixing tee air temperature, mixing tee metal temperature, and settling chamber metal temperature. Figure 8 illustrates the correspondence between simulated and actual responses for the mixing tee pressure and regulator station pressure. Figure 8 also shows the position of valve V3162 logged during the run, which is used as part of the dynamic input to the simulation.

Referring again to Figure 3, operating point 'C' is characterized by a settling chamber absolute pressure of 130 pounds per square inch, corresponding to a mass flow rate of 280 pounds per second. The desired settling chamber temperature is 100 degrees Fahrenheit.

Figures 9 and 10 show data for simulations of operating conditions 'D' and 'E', respectively. Valve 3292 is not used for these runs due to their low mass flow rate requirements. Point 'D' is characterized by a settling chamber absolute pressure of 130 pounds per square inch, corresponding to a mass flow rate of 40 pounds per second. The desired settling chamber temperature is 200 degrees Fahrenheit. Point 'E' is characterized by a settling chamber absolute pressure of 32 pounds per square inch, corresponding to a mass flow rate of 10 pounds per second. Similarly, the desired settling chamber temperature is 200 degrees Fahrenheit.

The simulation was also used to provide the expected tunnel responses to a 3.5% step change in position of valve V3292 as well as a single autotransformer tap change at operating point 'C'. These test conditions were not provided during any of the actual tunnel tests. Therefore, no comparison to actual tunnel data is provided. Figure 11 shows the simulated settling chamber and mixing tee pressure responses to a 3.5% step change of valve V3292. Figure 12 shows the corresponding simulated air temperature responses. Figure 13 shows the simulated settling chamber and mixing tee air temperature responses to a single tap change. Figure 14 shows the corresponding simulated pressure responses.

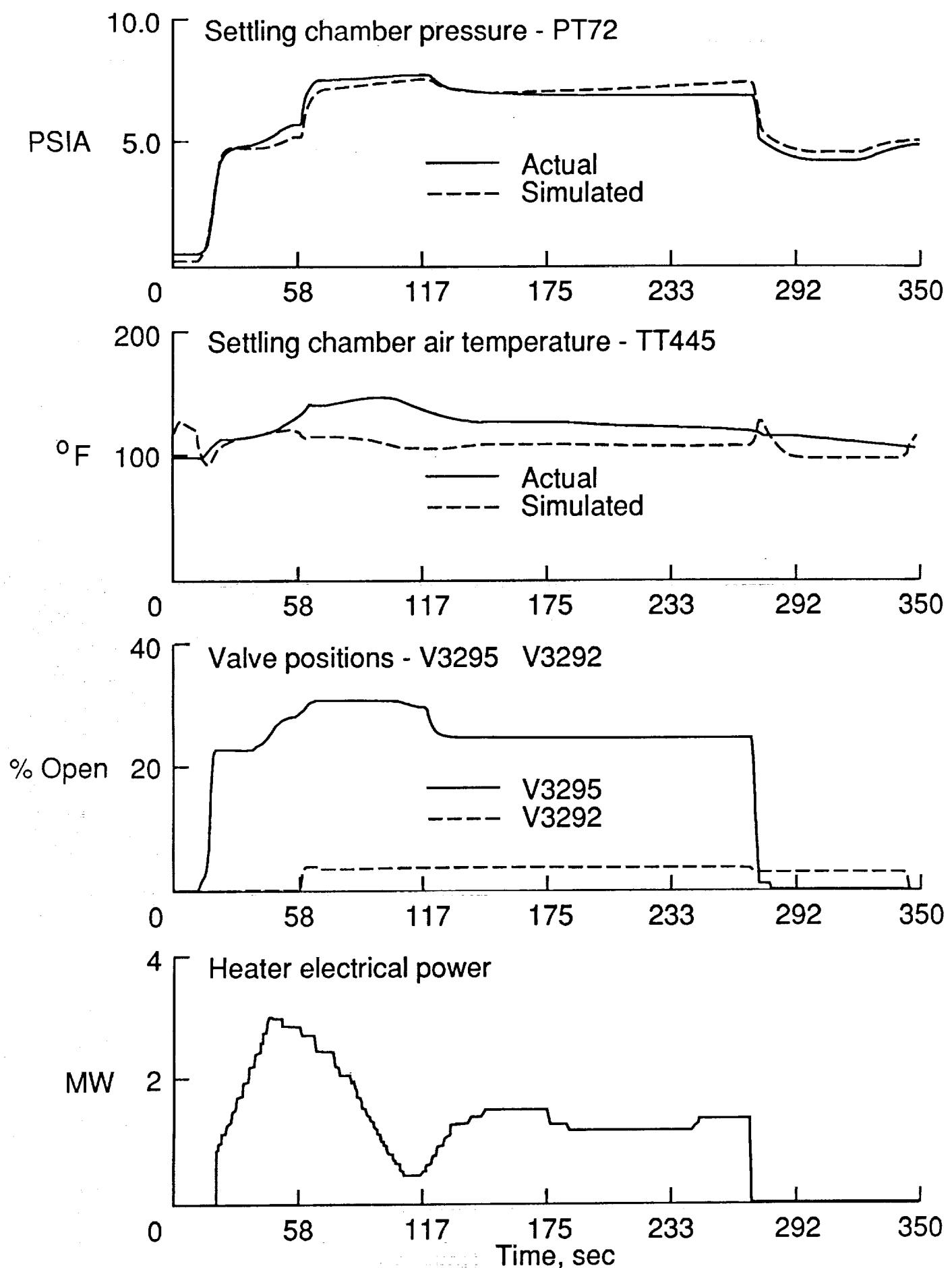
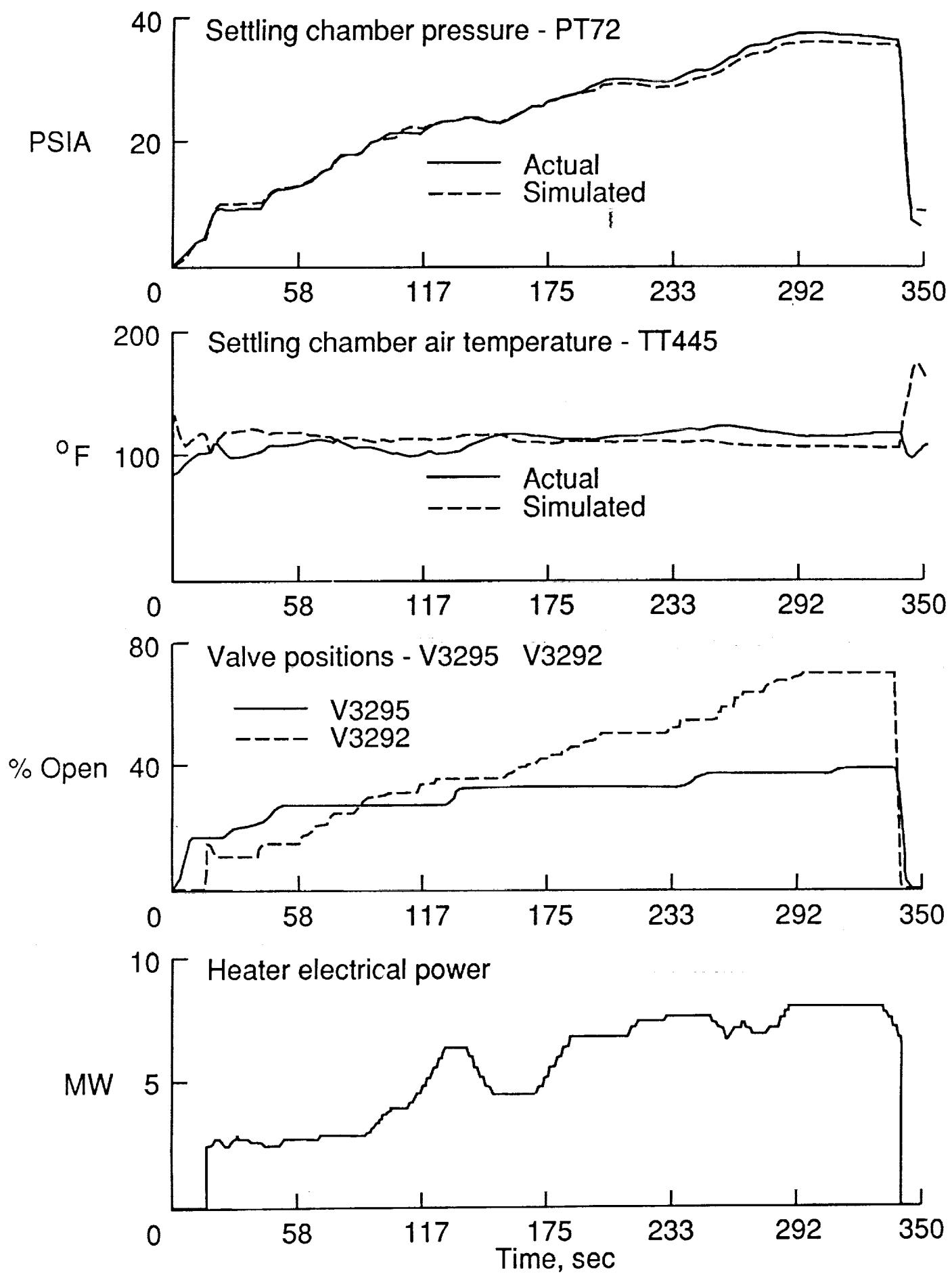


Figure 4. Simulated and Actual Responses - Pt A



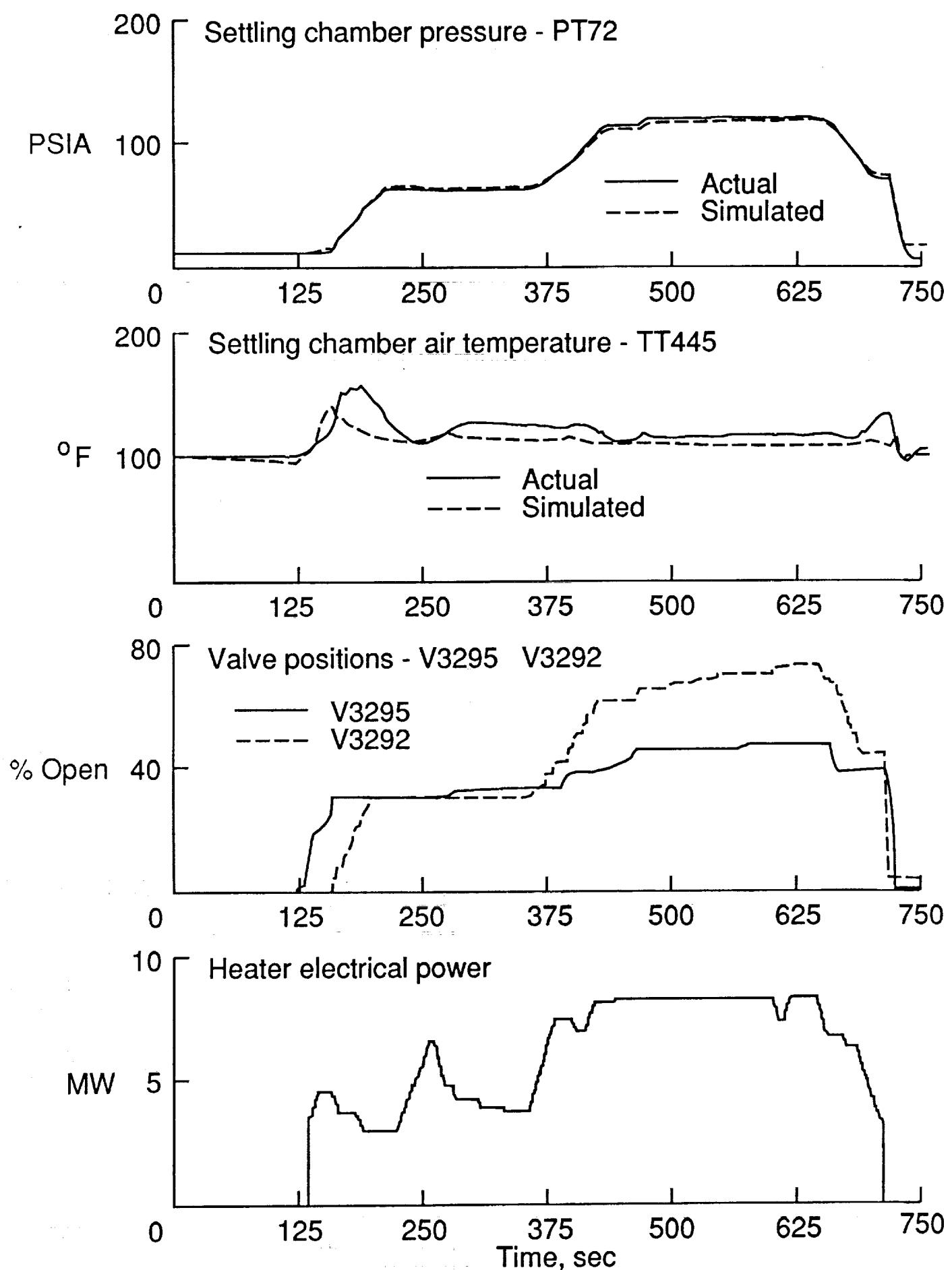
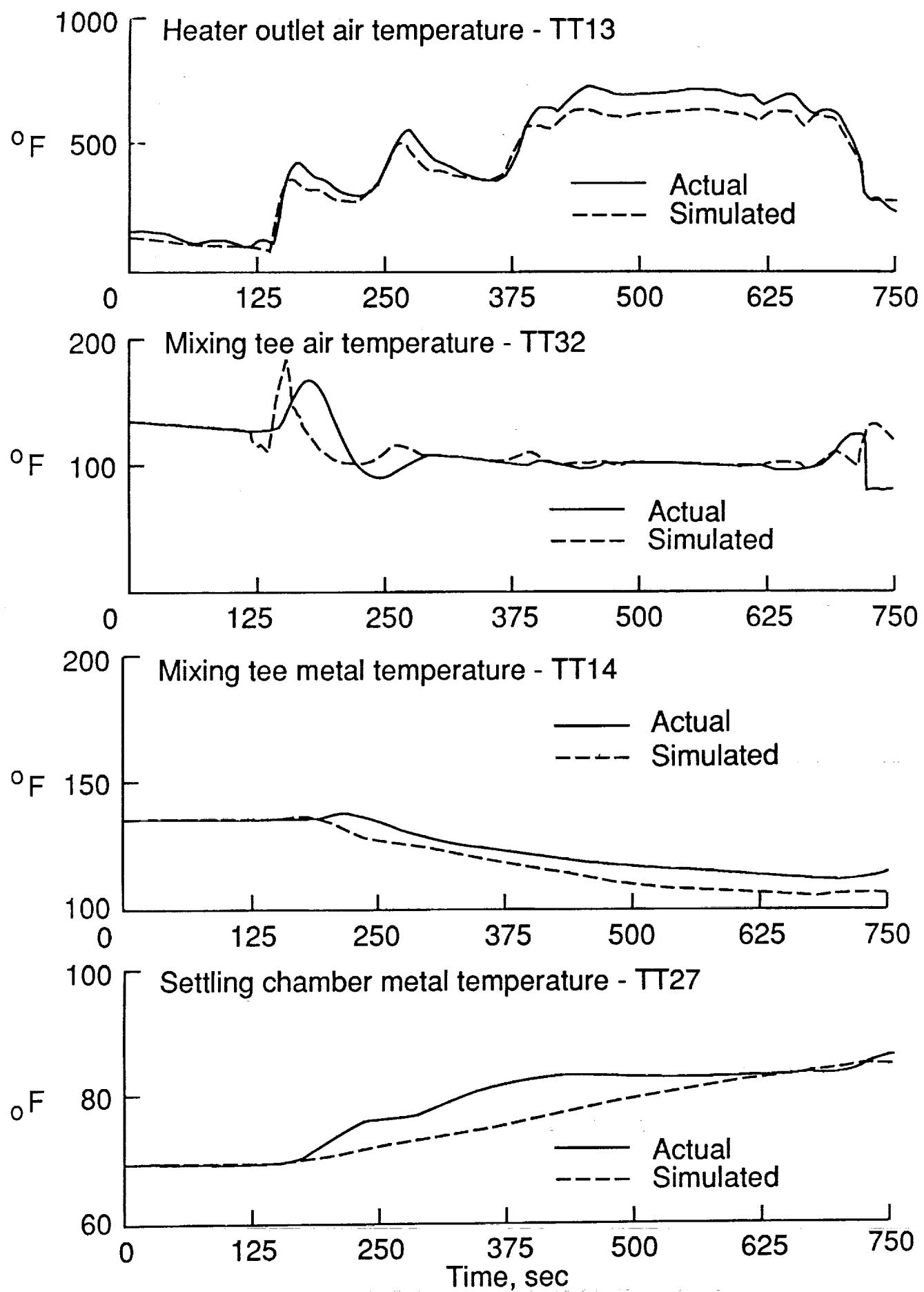


Figure 6. Simulated and Actual Responses - Pt C



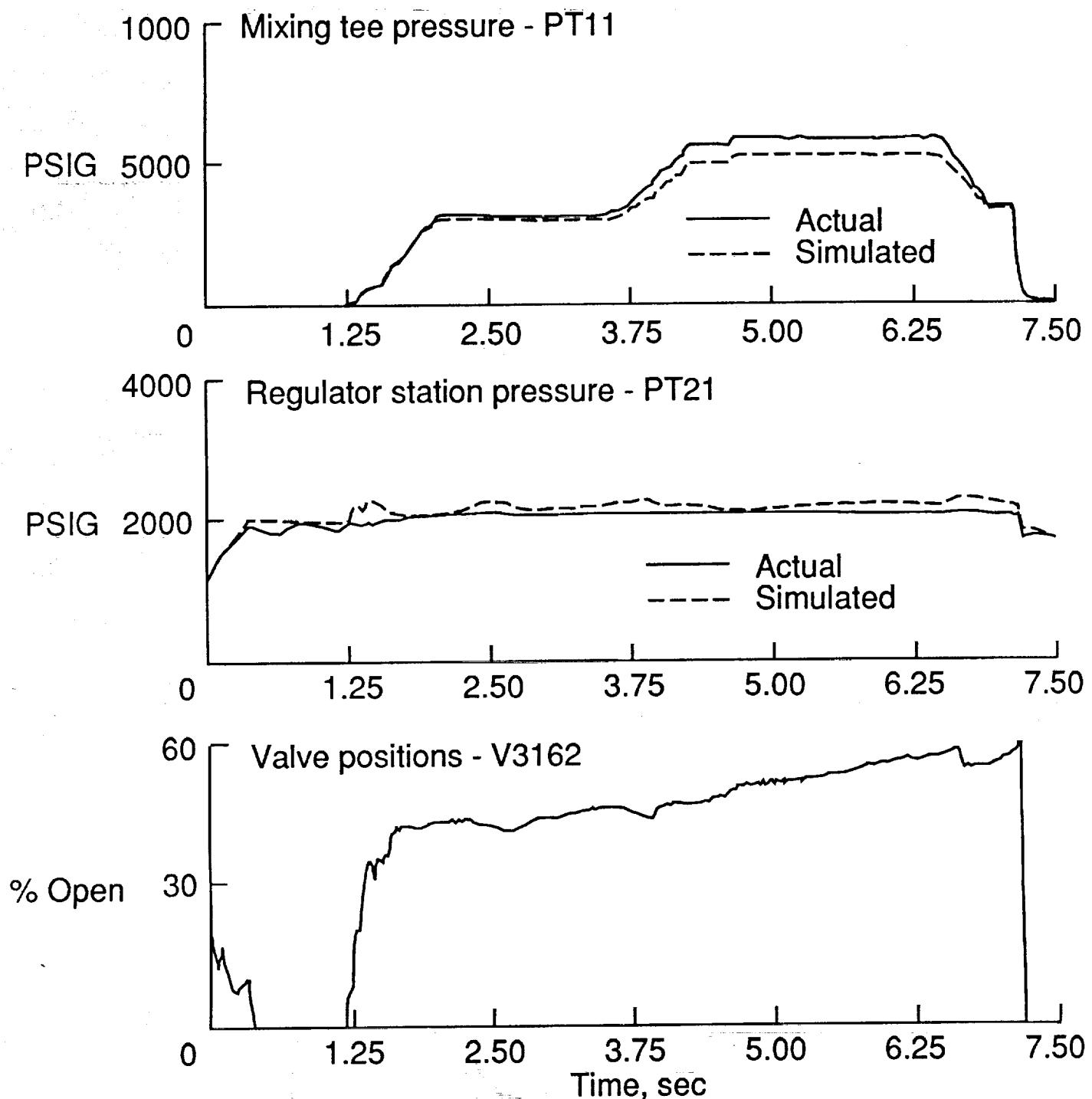
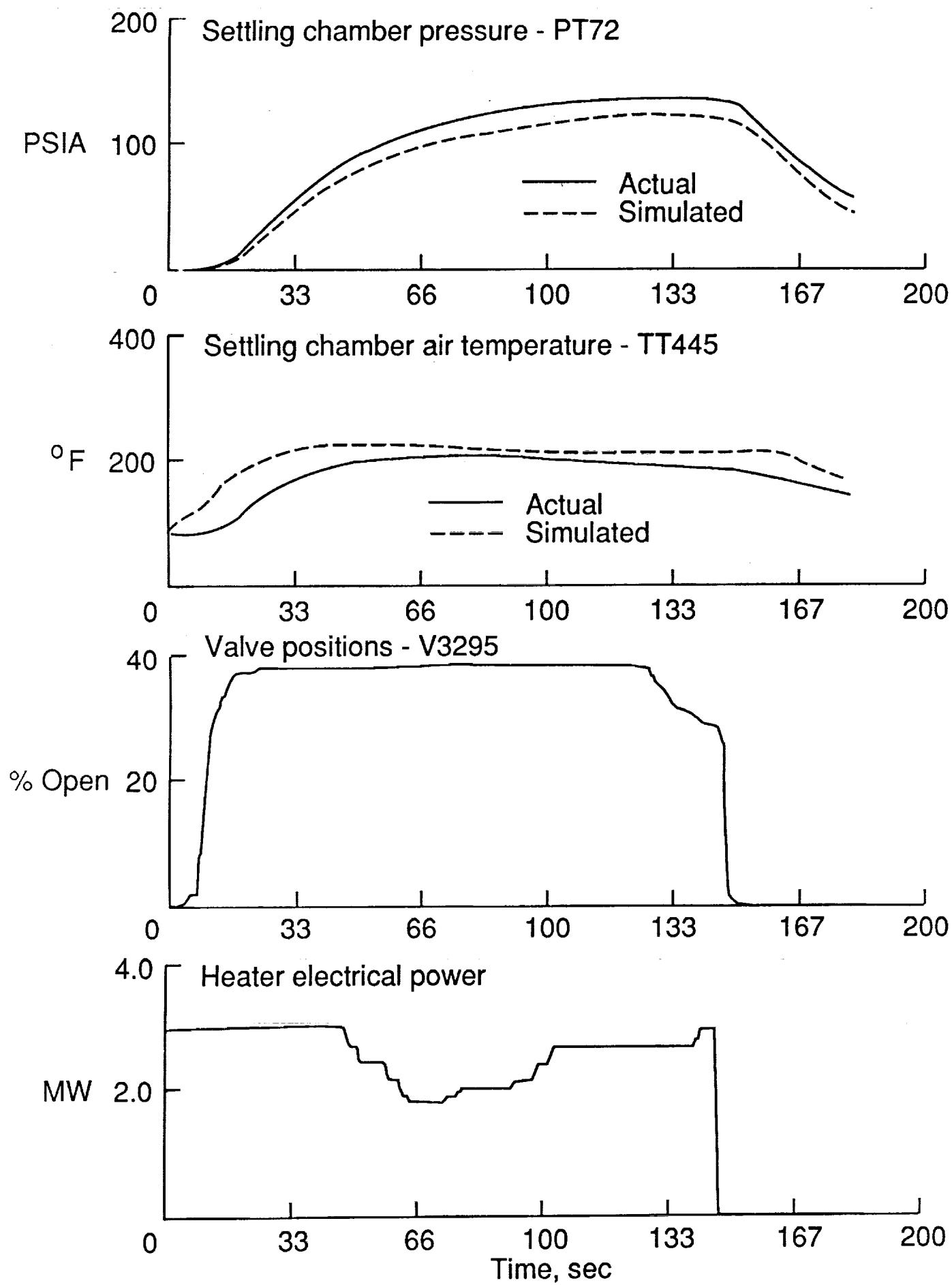


Figure 8. Simulated and Actual Responses - Pt C



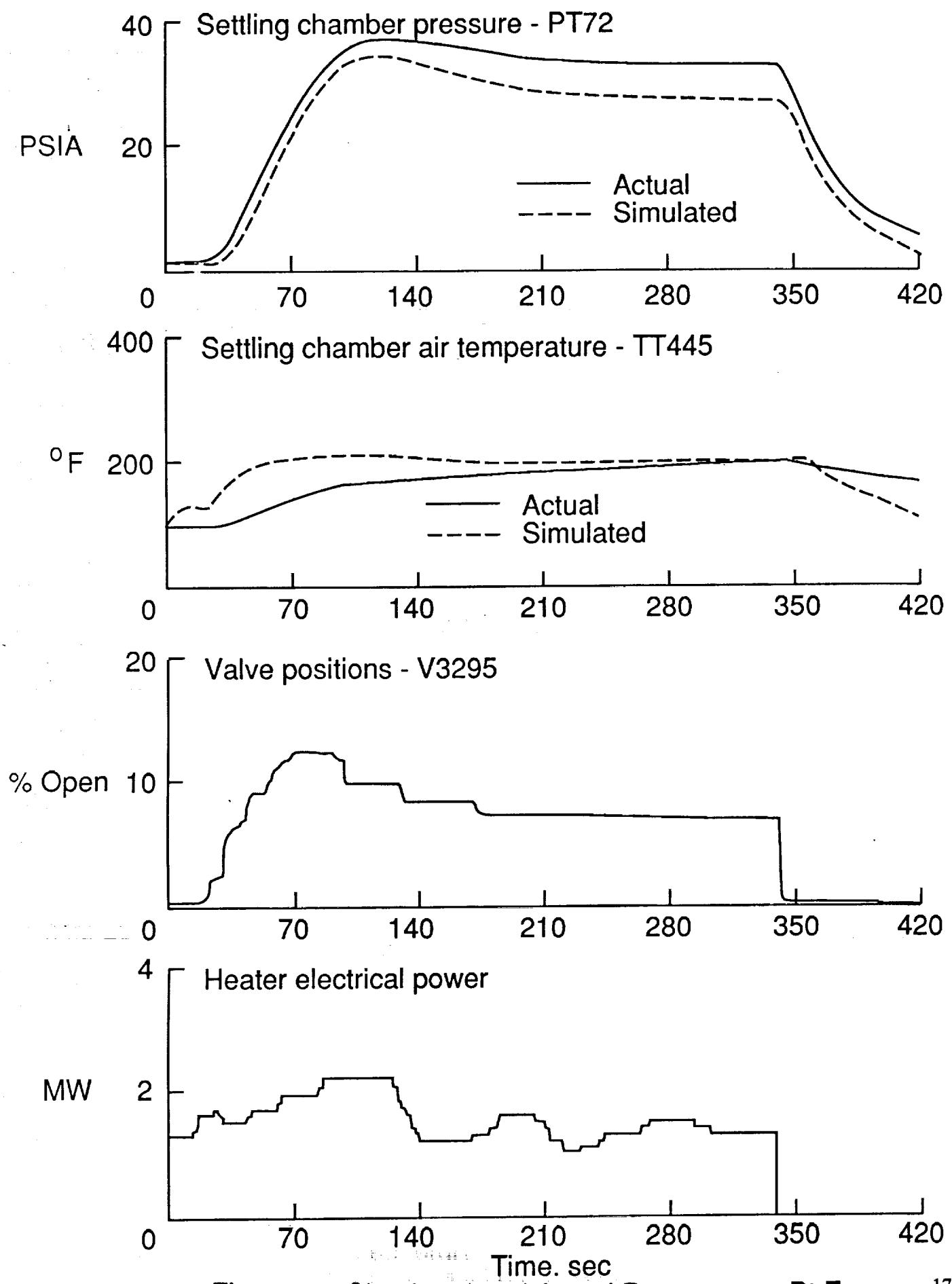
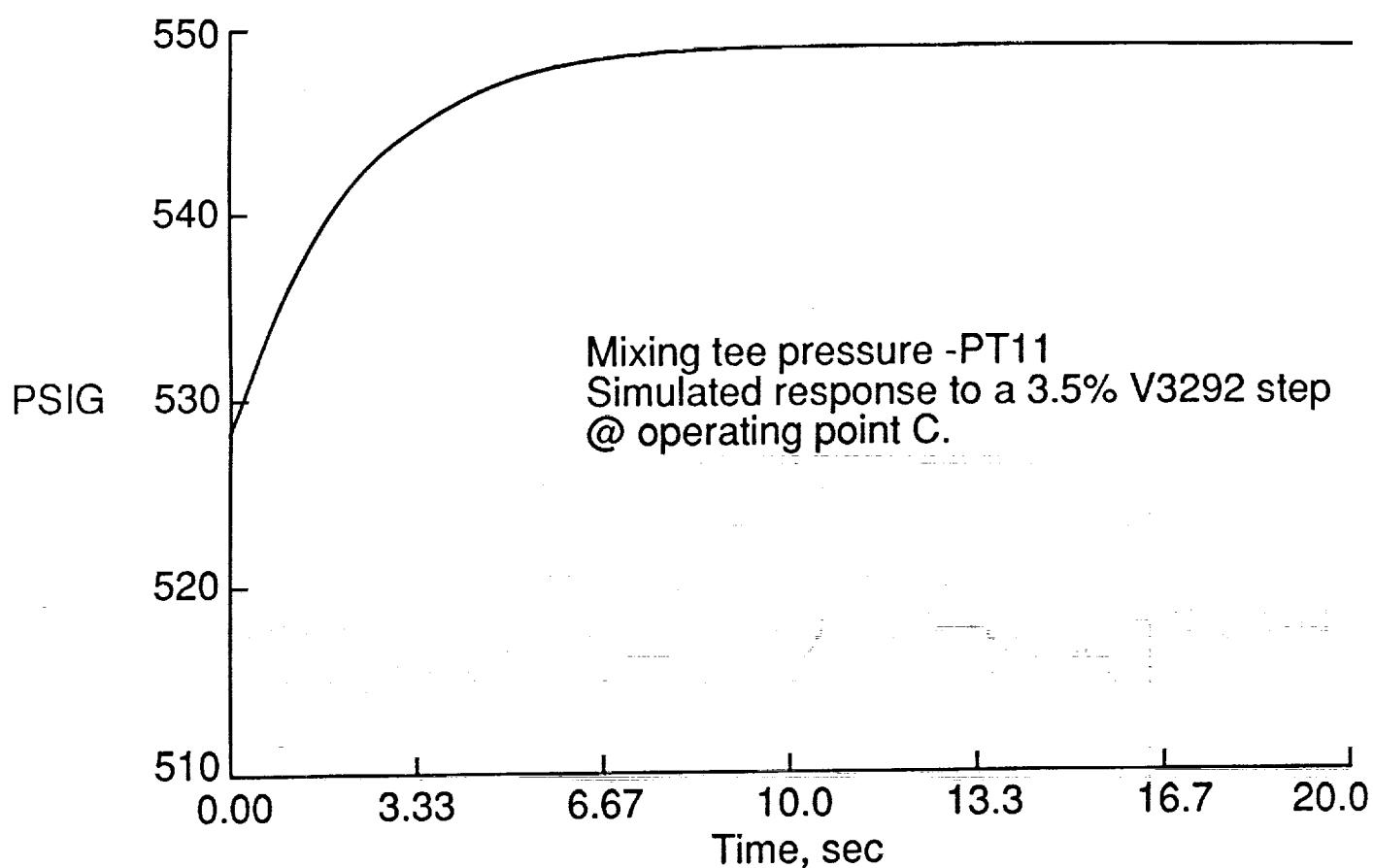
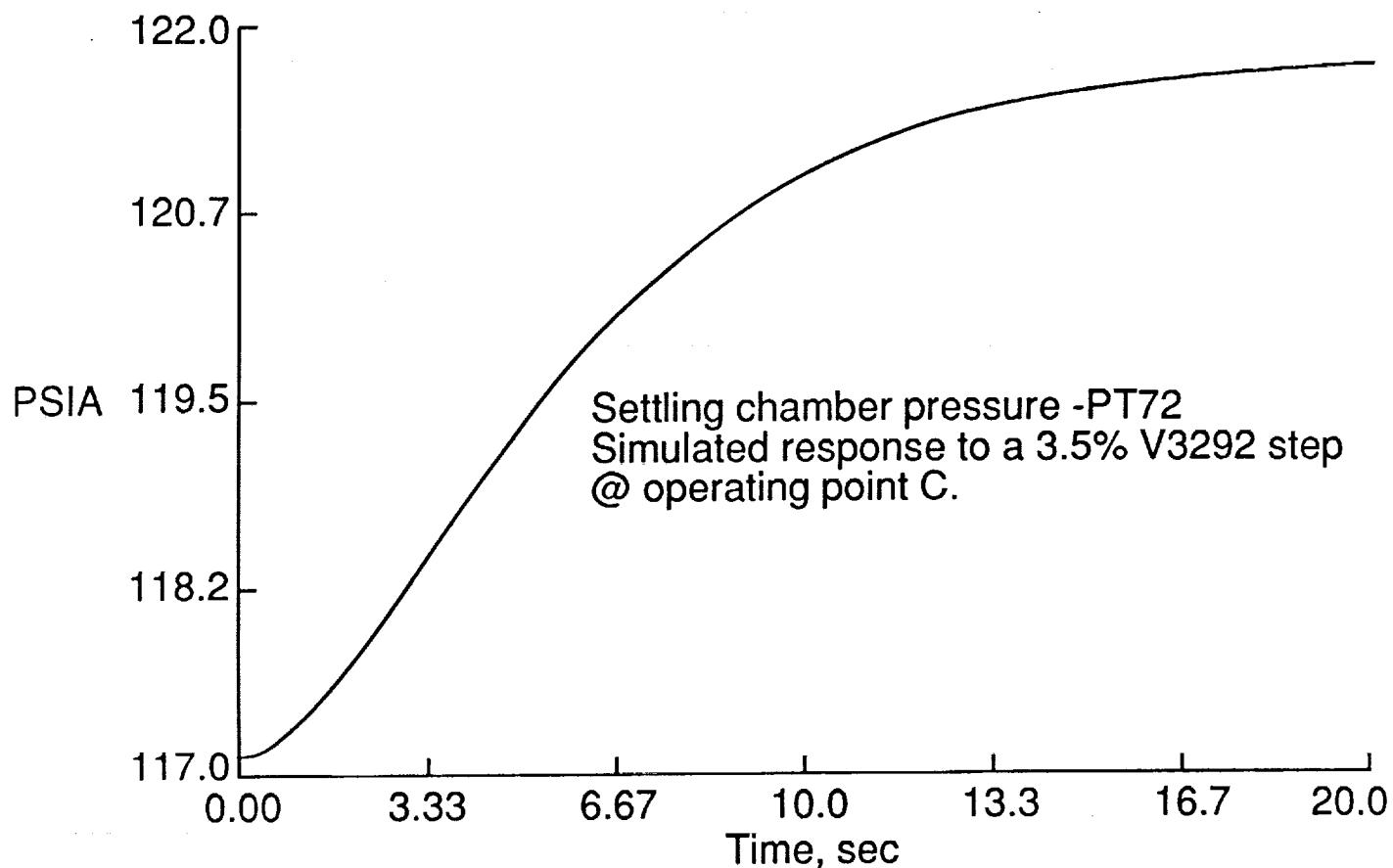


Figure 10. Simulated and Actual Responses - Pt E



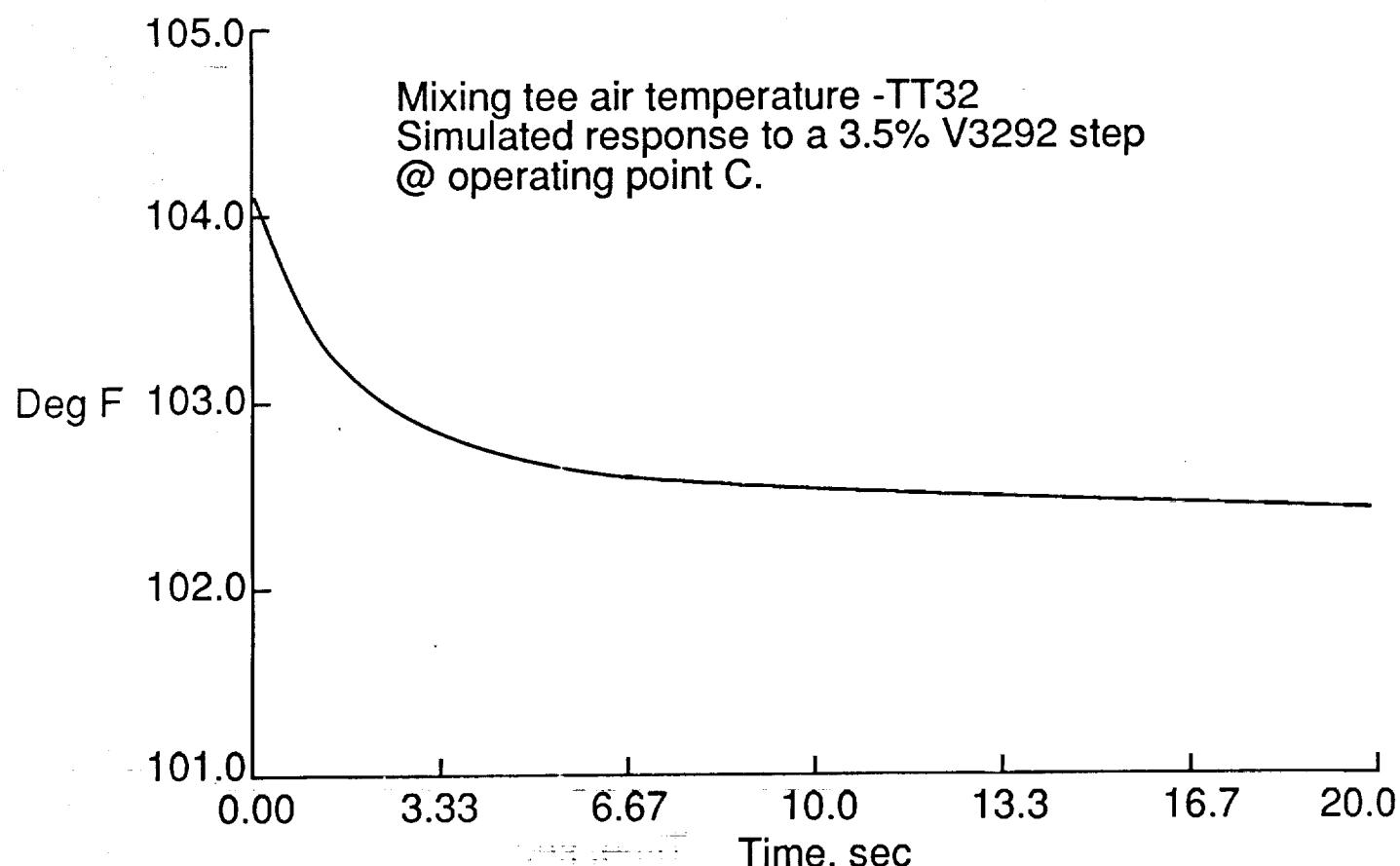
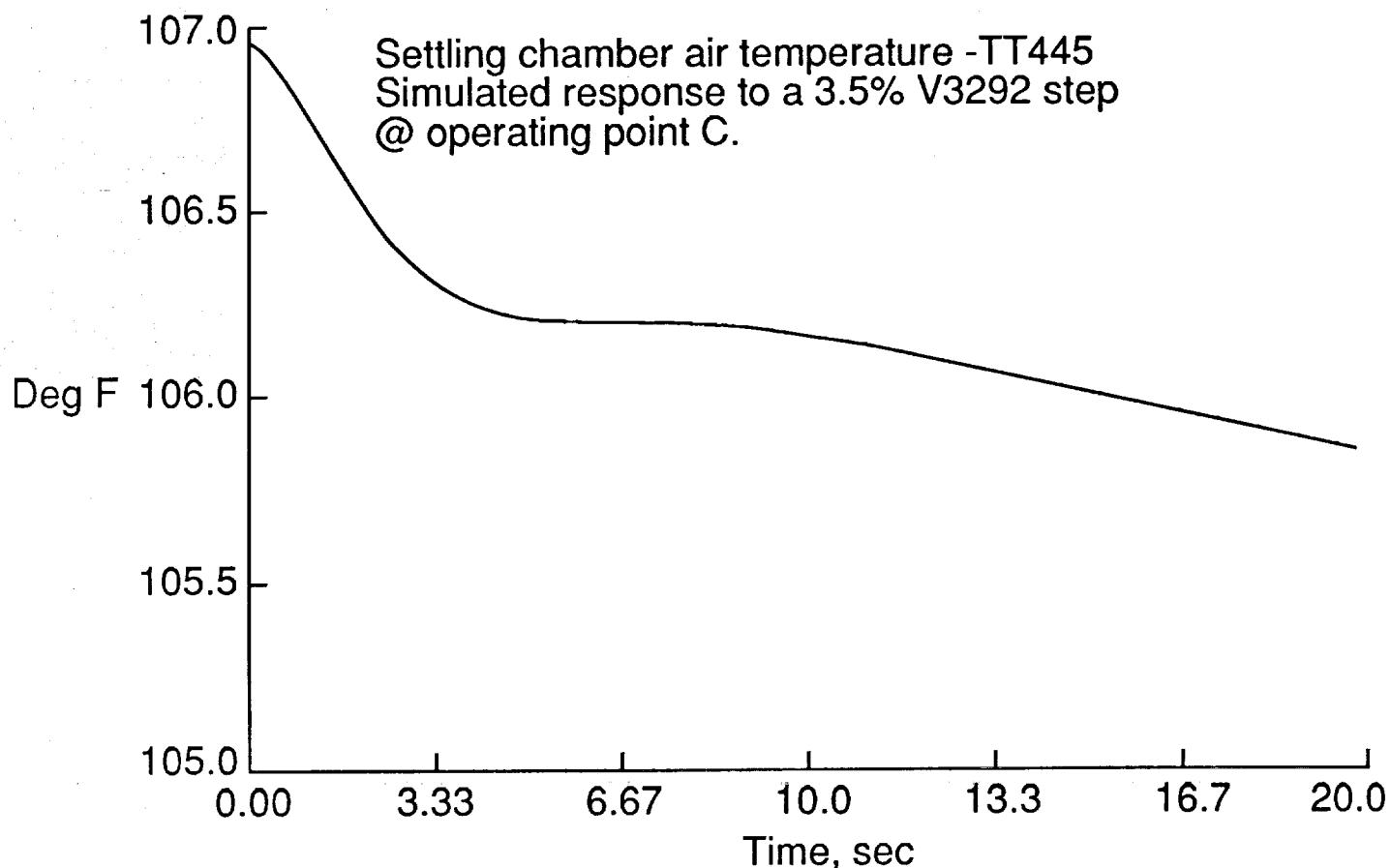
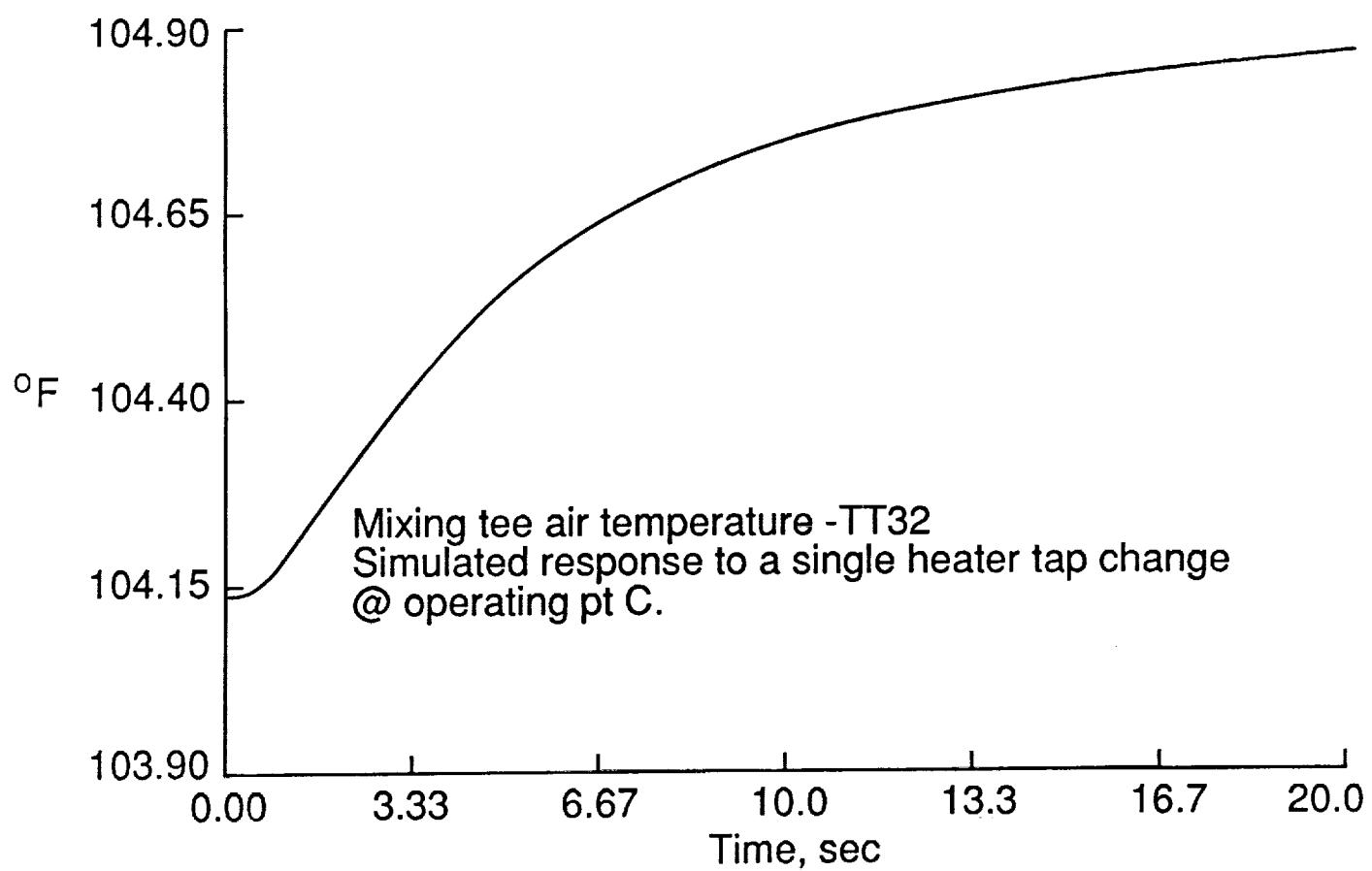
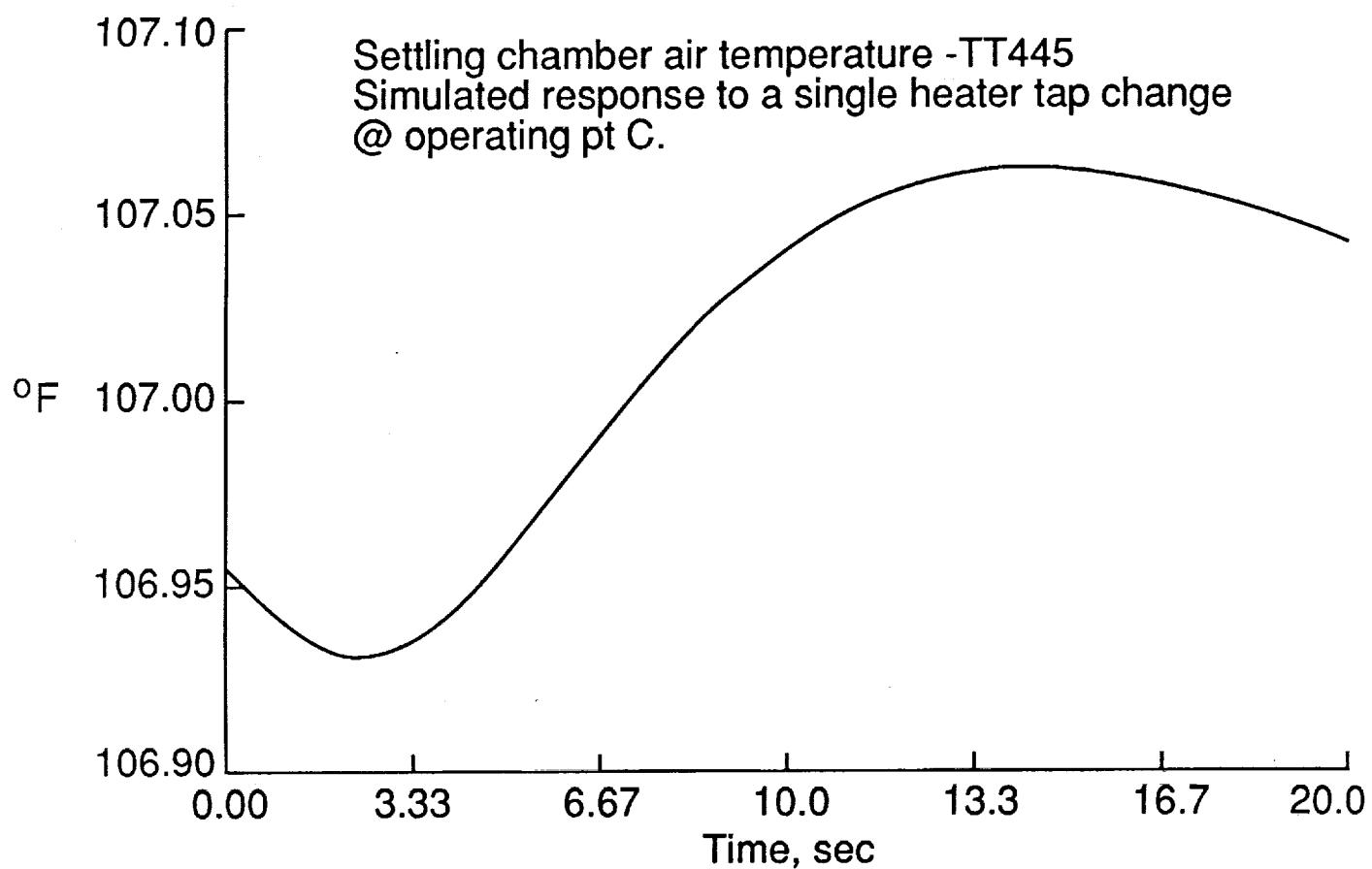


Figure 12. Simulated Temperature Responses - Pt C



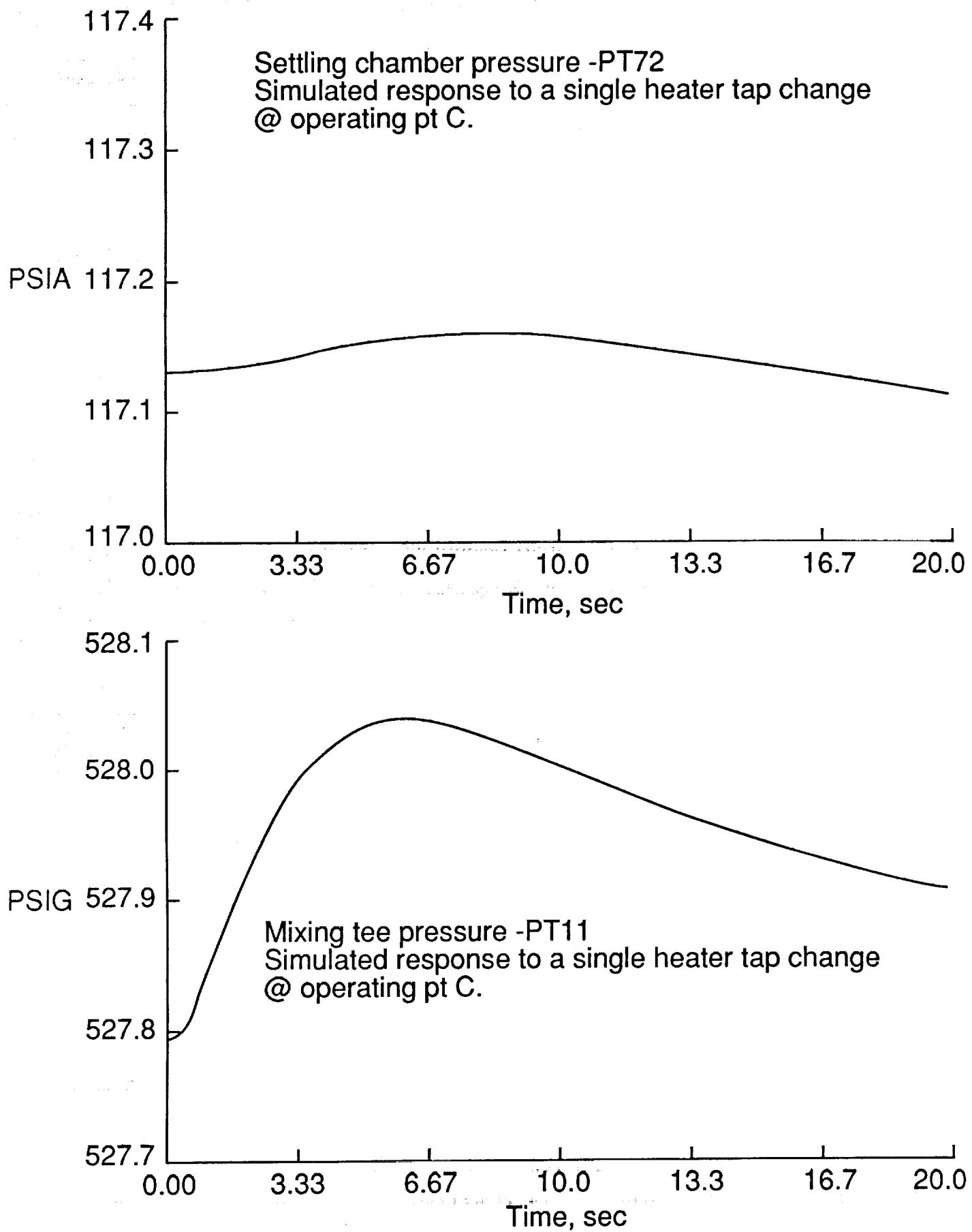


Figure 14. Simulated Pressure Responses - Pt C

Upon reaching steady state at each operating point, a linearized model and associated eigenvalues were evaluated using the ACSL 'ANALYZ' command. The 'FREEZE' command was used to eliminate the following variables from the state vector during the linearization:

| | | |
|--------|---|----------------------|
| BFENRG | - | Battlefield Energy |
| BFMAS | - | Battlefield Mass |
| VSENRG | - | Vacuum Sphere Energy |
| VSMAS | - | Vacuum Sphere Mass |

These states were associated with eigenvalues that were either zero or very close to the origin. The input vector was defined by the 'CONTRL' command as:

| | | |
|--------|---|----------------------------|
| VP3162 | - | V3162 Valve Position |
| VP3170 | - | V3170 Valve Position |
| VP3295 | - | V3295 Valve Position |
| VP3292 | - | V3292 Valve Position |
| IPOWER | - | M8 Heater Electrical Power |

The output vector was defined by the 'OBSERV' command as:

| | | |
|-------|---|-------------------------------|
| PT21 | - | Heater Upstream Pressure |
| PT11 | - | Mixing Tee Pressure |
| PT72 | - | Settling Chamber Pressure |
| TT13 | - | Heater Downstream Temperature |
| TT32 | - | Mixing Tee Air Temperature |
| TT445 | - | Settling Chamber Pressure |

Appendix A lists the operating point parameters, the ABC matrices for the linearized model, and the corresponding eigenvalues.

5.0 Conclusion

The development of a simulation of the pressure and temperature responses of the 20 Inch SWT has been presented. The simulation models the temperature and pressure responses based on initial conditions, valve positions, heater input power, and nozzle area. Results of typical simulation runs have been presented, illustrating the correspondence of simulated and actual tunnel responses. Deviations of the simulated temperature transient response from the actual temperature transients are attributed to the lumped-parameter characterization and the assumption of simple convective heat transfer between the air and surrounding vessels and piping. The simulated pressure transient responses follow the actual pressure transients quite well, with relatively small steady-state error.

The simulation has been used to determine a linearized model and corresponding eigenvalues for the five boundary points of the 20 Inch SWT operating map. The simulation contains elements common to other test cells using the Mach 8 Air Distribution System. Similar results for other test cells may be obtained by modification of the code describing the test cell elements.

6.0 References

1. Mitchell and Gauthier Associates: Advanced Continuous Simulation Language, Edition 4.1, Concord, Massachusetts, 1987.
2. Phillips, J.; and Owen-Jones, J. B.: Concise Applied Thermodynamics, D. Van Nostrand Company Ltd, London, 1966.
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4. Van Wylen, G. J.; and Sonntag, R. E.: Fundamentals of Classical Thermodynamics, Second Edition, John Wiley & Sons, New York, NY, 1978.
5. Fisher Controls: Control Valve Handbook, Fisher Controls International, Inc., Marshalltown, Iowa, 1977.

Appendix A

This appendix contains the numerical data pertinent to the linearized models determined for the five boundary points of the 20 Inch SWT operating map. For each operating point, the A , B , and C matrices are provided for the linear model:

$$\dot{x} = Ax + Bu;$$

$$y = Cx;$$

where

- x - state vector;
- u - input vector;
- y - output vector.

Table A-1. Model States, Inputs and Outputs

| <u>STATE VECTOR</u> | <u>INPUT VECTOR</u> | <u>OUTPUT VECTOR</u> |
|---------------------|---------------------|----------------------|
| HDENRG | VP3162 | PT21 |
| HDMAS | VP3170 | PT11 |
| HDTPIP | VP3295 | PT72 |
| HUENRG | VP3292 | TT13 |
| HUMAS | HPOWER | TT32 |
| HUTPIP | | TT445 |
| MTENRG | | |
| MTMAS | | |
| MTTPIP | | |
| PPENRG | | |
| PPTPIP | | |
| SCENRG | | |
| SCMAS | | |
| SCTPIP | | |
| TCORER | | |

The eigenvalues corresponding to the respective A matrix for each model are listed in Table A-2.

Operating Point 'A'

| | | | |
|------------|-------------|-----------------|-----------|
| Mach | 1.4 | Valve 3162 | 46.9 % |
| Flow | 50#/sec | Heater Upstream | 2060 PSIG |
| Psc | 7 PSIA | Valve 3295 | 24.7 % |
| Tsc | 100 degF | Valve 3292 | 3.5 % |
| A* | 322.9 in**2 | Mixing Tee | 99 PSIG |
| Valve 3296 | 7.1 in | Heater Power | 1.2 MW |
| Valve 3170 | 0.0 % | | |

PT 'A' B MATRIX ELEMENTS - ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|----|------------|------------|-----------|
| 1 | 0. | 0. | -2777.0800 | 0. | 0. |
| 2 | 0. | 0. | -79.097700 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 732.27800 | 0. | 0. | 0. | 0. |
| 5 | 162.37300 | 0. | 0. | 0. | 0. |
| 6 | -0.1050810 | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 2189.1500 | 3344.1400 | 0. |
| 8 | 0. | 0. | 79.097700 | 305.36700 | 0. |
| 9 | 0. | 0. | -0.0308547 | -0.0771601 | 0. |
| 10 | 0. | 0. | 102.31000 | 255.89000 | 0. |
| 11 | 0. | 0. | -0.0127871 | -0.0319863 | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 16.374600 |

PT 'A' C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|---|-----------|------------|------------|-----------|-----------|
| 1 | 0. | 0. | 0. | 0.1216600 | 9.5752200 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0.0143952 | -0.3601020 | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0.0114850 | 0.9023410 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0.0608321 | -1.0683800 | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0.0011533 | 0.0905492 | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0.0713649 | -1.3018600 | 0. | 0. |

PT 'A' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|------------|------------|------------|------------|
| 1 | -39.143500 | 608.50500 | 5.5600700 | 8.8942100 | 665.12600 |
| 2 | -0.1251930 | -9.8946400 | 0. | 0.2984480 | 23.580700 |
| 3 | 2.769E-04 | 0.0087502 | -0.0055601 | -5.277E-04 | -0.0248051 |
| 4 | 0.5475780 | 41.474900 | 0. | -2.3625600 | -94.493100 |
| 5 | 0.1247360 | 9.8113400 | 0. | -0.2991810 | -23.639200 |
| 6 | 2.759E-05 | 0.0028404 | 0. | 2.793E-04 | -0.0079257 |
| 7 | 0.0745869 | 0.2510310 | 0. | 0. | 0. |
| 8 | 4.583E-04 | 0.0833065 | 0. | 0. | 0. |
| 9 | -1.871E-07 | -3.407E-05 | 0. | 0. | 0. |
| 10 | 6.198E-04 | 0.1131430 | 0. | 0. | 0. |
| 11 | -7.750E-08 | -1.414E-05 | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0.6589010 | -11.500900 | 0. | -0.1149440 | -9.0828800 |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 24.471200 | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | -0.0102751 | 0. | 0. | 0. | 0. |
| 7 | 0. | -1.3078300 | 10.507000 | 14.559600 | 0. |
| 8 | 0. | -0.0026625 | -0.4644460 | 0. | 0. |
| 9 | 0. | 1.314E-04 | -0.0023075 | -0.0021715 | 0. |
| 10 | 0. | 0.7135500 | 16.943000 | 0. | -0.8080470 |
| 11 | 0. | 0. | -0.0021093 | 0. | 5.616E-05 |
| 12 | 0. | 0.0684784 | -1.5275100 | 0. | 0.3587340 |
| 13 | 0. | 0.0026625 | 0.4644460 | 0. | 0. |
| 14 | 0. | 4.242E-07 | 7.377E-05 | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 2452.7100 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 0. | 0. | 0. |
| 8 | 0. | 0. | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 14.823000 | 0. | 0. | 0. | 0. |
| 11 | -0.0018529 | 0. | 0. | 0. | 0. |
| 12 | 0. | -1.3538600 | -24.294500 | 1.2228700 | 0. |
| 13 | 0. | -0.0167117 | -1.6088100 | 0. | 0. |
| 14 | 0. | 2.202E-05 | -4.016E-04 | -3.054E-04 | 0. |
| 15 | 0. | 0. | 0. | 0. | -42.412400 |

Operating Point 'B'

| | | | |
|------------|-------------|-----------------|-----------|
| Mach | 1.4 | Valve 3162 | 52.5 % |
| Flow | 280#/sec | Heater Upstream | 2220 PSIG |
| Psc | 40 PSIA | Valve 3295 | 39.1 % |
| Tsc | 100 degF | Valve 3292 | 69.5 % |
| A* | 322.9 in**2 | Mixing Tee | 600 PSIG |
| Valve 3296 | 7.1 in | Heater Power | 8.1 MW |
| Valve 3170 | 0.0 % | | |

PT 'B' B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|----|------------|-----------|-----------|
| 1 | 0. | 0. | -15804.500 | 0. | 0. |
| 2 | 0. | 0. | -105.82000 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 944.45400 | 0. | 0. | 0. | 0. |
| 5 | 226.19200 | 0. | 0. | 0. | 0. |
| 6 | -0.1096730 | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 8782.7100 | 2897.7100 | 0. |
| 8 | 0. | 0. | 105.82000 | 307.84600 | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 0. | 0. | 0. | 0. | 0. |
| 11 | 0. | 0. | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 16.326900 |

PT 'B' C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|---|-----------|------------|------------|-----------|-----------|
| 1 | 0. | 0. | 0. | 0.1216520 | 9.5793400 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0.0223339 | -2.3813100 | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0.0114440 | 0.9020020 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0.0114086 | -0.1918390 | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0.0011508 | 0.0905721 | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0.0180486 | -0.3269550 | 0. | 0. |

PT 'B' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|------------|------------|------------|------------|
| 1 | -59.389200 | 3650.7200 | 9.5251800 | 34.356100 | 2811.7800 |
| 2 | -0.1195710 | -9.4999500 | 0. | 0.2849060 | 22.530400 |
| 3 | -0.0022929 | -0.2305860 | -0.0095247 | 0.0063100 | 0.3826790 |
| 4 | 0.4951250 | 39.792100 | 0. | -2.1883000 | -86.558300 |
| 5 | 0.1190920 | 9.3735800 | 0. | -0.2863780 | -22.646000 |
| 6 | 1.623E-05 | 9.321E-04 | 0. | 2.824E-04 | -0.0049001 |
| 7 | 0.1587990 | -3.3078700 | 0. | 0. | 0. |
| 8 | 4.794E-04 | 0.1263830 | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 0. | 0. | 0. | 0. | 0. |
| 11 | 0. | 0. | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 1.0518500 | -59.735400 | 0. | -0.6764980 | -53.507000 |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 28.591500 | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | -0.0120052 | 0. | 0. | 0. | 0. |
| 7 | 0. | -1.1435300 | 8.3894900 | 64.298700 | 0. |
| 8 | 0. | -0.0026573 | -0.4641080 | 0. | 0. |
| 9 | 0. | 9.367E-05 | -0.0016851 | -0.0082949 | 0. |
| 10 | 0. | 0.7126540 | 12.440800 | 0. | -0.6710530 |
| 11 | 0. | -5.752E-07 | -0.0015464 | 0. | 3.936E-05 |
| 12 | 0. | 0.0685044 | -1.1350300 | 0. | 0.3561730 |
| 13 | 0. | 0.0026573 | 0.4641080 | 0. | 0. |
| 14 | 0. | 0. | 3.782E-06 | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 1987.1400 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 1987.1400 |
| 6 | 0. | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 0. | 0. | 0. |
| 8 | 0. | 0. | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 55.552000 | 0. | 0. | 0. | 0. |
| 11 | -0.0069440 | 0. | 0. | 0. | 0. |
| 12 | 0. | -1.3179600 | 3.2130300 | 4.4906600 | 0. |
| 13 | 0. | -0.0041539 | -0.7294570 | 0. | 0. |
| 14 | 0. | 2.067E-05 | -3.236E-04 | -0.0011214 | 0. |
| 15 | 0. | 0. | 0. | 0. | -34.361700 |

Operating Point 'C'

| | | | |
|------------|------------|-----------------|-----------|
| Mach | 2.8 | Valve 3162 | 55.9 % |
| Flow | 280#/sec | Heater Upstream | 2090 PSIG |
| Psc | 130 PSIA | Valve 3295 | 47.5 % |
| Tsc | 100 degF | Valve 3292 | 71.4 % |
| A* | 95.8 in**2 | Mixing Tee | 575 PSIG |
| Valve 3296 | 7.1 in | Heater Power | 8.3 MW |

PT 'C' B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|----|------------|------------|-----------|
| 1 | 0. | 0. | -16769.200 | 0. | 0. |
| 2 | 0. | 0. | -105.74300 | 0. | 0. |
| 3 | 0. | 0. | 0.6820260 | 0. | 0. |
| 4 | 483.04800 | 0. | 0. | 0. | 0. |
| 5 | 208.14900 | 0. | 0. | 0. | 0. |
| 6 | -0.0060565 | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 9008.0700 | 2759.5700 | 0. |
| 8 | 0. | 0. | 105.74300 | 281.29600 | 0. |
| 9 | 0. | 0. | -0.0059791 | -0.0159163 | 0. |
| 10 | 0. | 0. | 98.114000 | 261.07800 | 0. |
| 11 | 0. | 0. | -0.0122562 | -0.0326335 | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 16.403200 |

PT 'C' C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|---|-----------|------------|------------|-----------|-----------|
| 1 | 0. | 0. | 0. | 0.1224640 | 9.5744800 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0.0251598 | -2.7272300 | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0.0114912 | 0.9021570 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0.0120183 | -0.2151880 | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0.0011524 | 0.0906312 | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0.0056342 | -0.1034530 | 0. | 0. |

PT 'C' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|------------|------------|------------|------------|
| 1 | -66.157300 | 4747.1300 | 8.7401100 | 31.864500 | 2417.3600 |
| 2 | -0.1020200 | -8.1409700 | 0. | 0.2443230 | 19.210300 |
| 3 | -1.148E-04 | -0.0498852 | -0.0087400 | 2.006E-05 | 0.0650455 |
| 4 | 0.2338170 | 18.417900 | 0. | -1.6362800 | -40.308800 |
| 5 | 0.1014430 | 7.9875000 | 0. | -0.2459560 | -19.340600 |
| 6 | 1.435E-06 | 1.098E-04 | 0. | 3.281E-04 | -8.267E-04 |
| 7 | 0.1950750 | -3.9513900 | 0. | 0. | 0. |
| 8 | 5.772E-04 | 0.1535380 | 0. | 0. | 0. |
| 9 | -3.255E-08 | -8.700E-06 | 0. | 0. | 0. |
| 10 | 5.333E-04 | 0.1418790 | 0. | 0. | 0. |
| 11 | -6.657E-08 | -1.772E-05 | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 1.1351200 | -81.383500 | 0. | -0.5359790 | -42.157900 |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 30.315000 | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | -0.0127288 | 0. | 0. | 0. | 0. |
| 7 | 0. | -1.1710000 | 8.8387500 | 62.697100 | 0. |
| 8 | 0. | -0.0026619 | -0.4644100 | 0. | 0. |
| 9 | 0. | 9.839E-05 | -0.0017616 | -0.0081914 | 0. |
| 10 | 0. | 0.7151690 | 12.227700 | 0. | -0.6872380 |
| 11 | 0. | 0. | -0.0015243 | 0. | 4.096E-05 |
| 12 | 0. | 0.0686162 | -1.4085900 | 0. | 0.3595510 |
| 13 | 0. | 0.0026619 | 0.4644100 | 0. | 0. |
| 14 | 0. | 2.252E-07 | 3.904E-05 | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 2092.6200 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 0. | 0. | 0. |
| 8 | 0. | 0. | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 54.589200 | 0. | 0. | 0. | 0. |
| 11 | -0.0068236 | 0. | 0. | 0. | 0. |
| 12 | 0. | -0.3923630 | 1.0391900 | 4.3711100 | 0. |
| 13 | 0. | -0.0012334 | -0.2165930 | 0. | 0. |
| 14 | 0. | 6.202E-06 | -1.139E-04 | -0.0010916 | 0. |
| 15 | 0. | 0. | 0. | 0. | -36.185700 |

Operating Point 'D'

| | | | |
|------------|------------|-----------------|-----------|
| Mach | 5.0 | Valve 3162 | 41.4 % |
| Flow | 40 #/sec | Heater Upstream | 1864 PSIG |
| Psc | 130 PSIA | Valve 3295 | 30.9 % |
| Tsc | 200 degF | Valve 3292 | 0.0 % |
| A* | 14.4 in**2 | Mixing Tee | 610 PSIG |
| Valve 3296 | 1.1 in | Heater Power | 2.8 MW |
| Valve 3170 | 0.0 % | | |

PT 'D' B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|----|------------|----|-----------|
| 1 | 0. | 0. | -4998.4700 | 0. | 0. |
| 2 | 0. | 0. | -86.307500 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | -263.55700 | 0. | 0. | 0. | 0. |
| 5 | 190.33400 | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 4493.7900 | 0. | 0. |
| 8 | 0. | 0. | 86.307500 | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 0. | 0. | 0. | 0. | 0. |
| 11 | 0. | 0. | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 16.365100 |

PT 'D' C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|---|-----------|------------|------------|-----------|-----------|
| 1 | 0. | 0. | 0. | 0.1221430 | 9.5816600 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0.0220652 | -0.9105040 | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0.0114606 | 0.9023500 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0.0162818 | -0.5899490 | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0.0011503 | 0.0906466 | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0.0062491 | -0.2202930 | 0. | 0. |

PT 'D' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|------------|------------|------------|------------|
| 1 | -51.248600 | 1456.3500 | 5.8692600 | 13.305600 | 1026.0600 |
| 2 | -0.1080210 | -8.5679700 | 0. | 0.2579560 | 20.339700 |
| 3 | -2.957E-04 | -0.0389259 | -0.0058692 | 0.0010232 | 0.0806849 |
| 4 | -0.0747402 | -2.3153500 | 0. | -0.8626810 | 2.8108300 |
| 5 | 0.1074500 | 8.4546200 | 0. | -0.2581310 | -20.352000 |
| 6 | 1.128E-04 | 0.0073820 | 0. | 5.357E-05 | -0.0157330 |
| 7 | 0.1030180 | 1.3139600 | 0. | 0. | 0. |
| 8 | 4.829E-04 | 0.0960792 | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 0. | 0. | 0. | 0. | 0. |
| 11 | 0. | 0. | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0.8840600 | -24.750600 | 0. | -0.2347000 | -18.509400 |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 22.268400 | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | -0.0093502 | 0. | 0. | 0. | 0. |
| 7 | 0. | -0.2661280 | 4.9632400 | 10.579000 | 0. |
| 8 | 0. | -4.150E-04 | -0.0804379 | 0. | 0. |
| 9 | 0. | 2.798E-05 | -0.0010322 | -0.0017270 | 0. |
| 10 | 0. | 0.1318150 | 7.3023200 | 0. | -0.1648080 |
| 11 | 0. | 1.307E-07 | -9.076E-04 | 0. | 1.223E-05 |
| 12 | 0. | 0.0222233 | -0.8058670 | 0. | 0.0670078 |
| 13 | 0. | 4.150E-04 | 0.0804379 | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 2058.9300 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 0. | 0. | 0. |
| 8 | 0. | 0. | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 11.972600 | 0. | 0. | 0. | 0. |
| 11 | -0.0014966 | 0. | 0. | 0. | 0. |
| 12 | 0. | -0.0704947 | 0.4812590 | 1.1187200 | 0. |
| 13 | 0. | -1.707E-04 | -0.0329318 | 0. | 0. |
| 14 | 0. | 1.855E-06 | -4.634E-05 | -2.794E-04 | 0. |
| 15 | 0. | 0. | 0. | 0. | -35.603100 |

Operating Point 'E'

| | | | |
|------------|------------|-----------------|-----------|
| Mach | 5.0 | Valve 3162 | 24.0 % |
| Flow | 10 #/sec | Heater Upstream | 1103 PSIG |
| Psc | 32 PSIA | Valve 3295 | 10.0 % |
| Tsc | 200 degF | Valve 3292 | 0.0 % |
| A* | 14.4 in**2 | Mixing Tee | 147 PSIG |
| Valve 3296 | 1.1 in | Heater Power | 2.2 MW |
| Valve 3170 | 11.9 % | | |

PT 'E' B MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|------------|------------|----|-----------|
| 1 | 0. | -4023.8500 | -5896.3000 | 0. | 0. |
| 2 | 0. | -41.408500 | -60.677500 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 110.71000 | 0. | 0. | 0. | 0. |
| 5 | 81.076600 | 0. | 0. | 0. | 0. |
| 6 | -0.1744370 | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 4293.3400 | 0. | 0. |
| 8 | 0. | 0. | 60.677500 | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 0. | 0. | 0. | 0. | 0. |
| 11 | 0. | 0. | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 16.365100 |

PT 'E' C MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|---|-----------|------------|------------|-----------|-----------|
| 1 | 0. | 0. | 0. | 0.1218830 | 9.5785800 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0.0373288 | -2.5845200 | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0.0114619 | 0.9028180 | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0.0560671 | -2.3460100 | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0.0011530 | 0.0905970 | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0.0225549 | -0.8012540 | 0. | 0. |

PT 'E' A MATRIX ELEMENTS—ROWS ACROSS, COLUMNS DOWN

| | 1 | 2 | 3 | 4 | 5 |
|----|------------|------------|------------|------------|------------|
| 1 | -49.114900 | 1296.4600 | 4.0050300 | 34.101300 | 2672.1700 |
| 2 | -0.1781320 | -14.076000 | 0. | 0.4262190 | 33.569800 |
| 3 | -0.0052256 | -0.4338660 | -0.0040050 | 0.0128898 | 1.0152200 |
| 4 | 0.0869982 | 6.3051200 | 0. | -1.8584200 | -8.9053900 |
| 5 | 0.1778030 | 14.001300 | 0. | -0.4262140 | -33.569800 |
| 6 | 1.641E-04 | 0.0131515 | 0. | 2.294E-04 | -0.0336915 |
| 7 | 0.0587260 | 0.2415530 | 0. | 0. | 0. |
| 8 | 2.147E-04 | 0.0486974 | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 0. | 0. | 0. | 0. | 0. |
| 11 | 0. | 0. | 0. | 0. | 0. |
| 12 | 0. | 0. | 0. | 0. | 0. |
| 13 | 0. | 0. | 0. | 0. | 0. |
| 14 | 0. | 0. | 0. | 0. | 0. |
| 15 | 0.9284760 | -15.528500 | 0. | -0.7897580 | -62.208600 |
| | 6 | 7 | 8 | 9 | 10 |
| 1 | 0. | 0. | 0. | 0. | 0. |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 11.352300 | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | -0.0047667 | 0. | 0. | 0. | 0. |
| 7 | 0. | -0.3288400 | 7.2087200 | 4.0953800 | 0. |
| 8 | 0. | -4.058E-04 | -0.0808637 | 0. | 0. |
| 9 | 0. | 4.204E-05 | -0.0015492 | -7.270E-04 | 0. |
| 10 | 0. | 0.1369760 | 9.2562600 | 0. | -0.1989430 |
| 11 | 0. | 3.097E-07 | -0.0011681 | 0. | 1.629E-05 |
| 12 | 0. | 0.0203134 | -1.1380400 | 0. | 0.0686673 |
| 13 | 0. | 4.058E-04 | 0.0808637 | 0. | 0. |
| 14 | 0. | 2.980E-07 | 5.935E-05 | 0. | 0. |
| 15 | 0. | 0. | 0. | 0. | 0. |
| | 11 | 12 | 13 | 14 | 15 |
| 1 | 0. | 0. | 0. | 0. | 926.88000 |
| 2 | 0. | 0. | 0. | 0. | 0. |
| 3 | 0. | 0. | 0. | 0. | 0. |
| 4 | 0. | 0. | 0. | 0. | 0. |
| 5 | 0. | 0. | 0. | 0. | 0. |
| 6 | 0. | 0. | 0. | 0. | 0. |
| 7 | 0. | 0. | 0. | 0. | 0. |
| 8 | 0. | 0. | 0. | 0. | 0. |
| 9 | 0. | 0. | 0. | 0. | 0. |
| 10 | 4.6158300 | 0. | 0. | 0. | 0. |
| 11 | -5.770E-04 | 0. | 0. | 0. | 0. |
| 12 | 0. | -0.0727939 | 0.6418340 | 0.4164470 | 0. |
| 13 | 0. | -1.711E-04 | -0.0329319 | 0. | 0. |
| 14 | 0. | 2.380E-06 | -8.454E-05 | -1.040E-04 | 0. |
| 15 | 0. | 0. | 0. | 0. | -16.027700 |

Table A-2 Eigenvalues
PT 'A' COMPLEX EIGENVALUES IN ASCENDING ORDER

REAL

| | |
|----|-------------|
| 1 | -2.7630E-04 |
| 2 | -6.3167E-04 |
| 3 | -8.2154E-04 |
| 4 | -0.00232002 |
| 5 | -0.00267969 |
| 6 | -0.07930920 |
| 7 | -0.15291600 |
| 8 | -0.49909500 |
| 9 | -0.80907900 |
| 10 | -0.83155300 |
| 11 | -1.11525000 |
| 12 | -1.27472000 |
| 13 | -2.13115000 |
| 14 | -35.1432000 |
| 15 | -80.9724000 |

PT 'B' COMPLEX EIGENVALUES IN ASCENDING ORDER

| | REAL | IMAGINARY | FREQUENCY | DAMPING |
|----|-------------|---------------|-----------|----------|
| 1 | -0.00104569 | | | |
| 2 | -0.00270519 | | | |
| 3 | -0.00280500 | | | |
| 4 | -0.00366776 | | | |
| 5 | -0.00634853 | | | |
| 6 | -0.13960600 | +/-0.08697920 | 0.164485 | 0.848748 |
| 8 | -0.49894000 | | | |
| 9 | -0.67433000 | | | |
| 10 | -0.75309400 | | | |
| 11 | -1.02034000 | | | |
| 12 | -1.11429000 | | | |
| 13 | -1.29440000 | | | |
| 14 | -33.5545000 | | | |
| 15 | -93.2435000 | | | |

PT 'C' COMPLEX EIGENVALUES IN ASCENDING ORDER

| | REAL |
|----|--------------|
| 1 | -0.00101619 |
| 2 | -0.00261037 |
| 3 | -0.00355310 |
| 4 | -0.00363841 |
| 5 | -0.00461733 |
| 6 | --0.16323700 |
| 7 | --0.22422700 |
| 8 | -0.24605300 |
| 9 | -0.38480500 |
| 10 | -0.49969000 |
| 11 | -0.69050900 |
| 12 | -1.09308000 |
| 13 | -1.14130000 |
| 14 | -31.0387000 |
| 15 | -98.9331000 |

PT 'D' COMPLEX EIGEN VALUES IN ASCENDING ORDER

| | REAL |
|----|-------------|
| 1 | -2.4714E-04 |
| 2 | -5.1650E-04 |
| 3 | -6.0521E-04 |
| 4 | -0.00248492 |
| 5 | -0.00393938 |
| 6 | -0.03526640 |
| 7 | -0.06819240 |
| 8 | -0.08323000 |
| 9 | -0.09235360 |
| 10 | -0.16569900 |
| 11 | -0.16647600 |
| 12 | -0.25542300 |
| 13 | -0.92102400 |
| 14 | -29.4508000 |
| 15 | -86.0216000 |

OPERATING POINT 'E' COMPLEX EIGENVALUES IN ASCENDING ORDER

| | REAL |
|----|-------------|
| 1 | -8.8553E-05 |
| 2 | -1.6777E-04 |
| 3 | -1.9877E-04 |
| 4 | -4.8855E-04 |
| 5 | -0.00185111 |
| 6 | -0.03591100 |
| 7 | -0.05460000 |
| 8 | -0.06983020 |
| 9 | -0.09330200 |
| 10 | -0.10376900 |
| 11 | -0.19932200 |
| 12 | -0.31696100 |
| 13 | -1.71268000 |
| 14 | -36.3505000 |
| 15 | -76.4317000 |

APPENDIX B
Simulation Source Code Listing

Program 20IN

Initial

Macro QNRG(X,TGdegR,TMdegR,FLO)

' This macro calculates the rate of heat energy transferred out ' of a volume to the surrounding pipe mass'

```

X_TFLM = (TGdegR + TMdegR) * 0.5
X_CPG = .23777 - 4.75178E-8 * TGdegR
X_MUG = .00692 + 7.78859E-5 * TGdegR
X_KG = .00075 + 2.91114E-5 * TGdegR
X_MUF = .00692 + 7.78859E-5 * X_TFLM
X_PR = X_CPG * X_MUG/X_KG
X_FLOW = ABS(FLO)
X_RE = XK2/X_DIA * X_FLOW/X_MUF * TGdegR/X_TFLM
X_U = XK1/X_DIA * X_KG * X_PR**TEXP * X_RE**QEXP
X_QNRG = X_U * X_AREA * (TGdegR-TMdegR)

```

Macro end

Macro M8HETR(X,TGdegR,TMdegR,FLO)

' This macro calculates the rate of heat energy delivered ' by the M8 Heater'

```

X_TFLM = (TGdegR + TMdegR) * 0.5
X_CPG = .23777 - 4.75178E-8 * TGdegR
X_MUG = .00692 + 7.78859E-5 * TGdegR
X_KG = .00075 + 2.91114E-5 * TGdegR
X_MUF = .00692 + 7.78859E-5 * X_TFLM
X_PR = X_CPG * X_MUG/X_KG
X_FLOW = ABS(FLO)
X_RE = XK2/X_DIA * 0.00463 * X_FLOW/X_MUF * TGdegR/X_TFLM
X_U = XK1/X_DIA * 216.0 * * X_KG * X_PR**TEXP * X_RE**QEXP
X_DELT = (TGdegR-TMdegR)
X_QNRG = X_U * X_AREA * (TGdegR-TMdegR)

```

Macro end

'*****External Data Reading Capability*****'

Logical REXDAT

Constant REXDAT=.FALSE.

'Set REXDAT to .TRUE. to read external data'

'Variables from the gaslab logging file'

ARRAY EXDATA(31)

```

EQUIVALENCE (EXDATA(1),TIMEX),(EXDATA(2),PT33X),...
  (EXDATA(3),PT21X),...
  (EXDATA(4),PT42X),(EXDATA(5),PT45X),...
  (EXDATA(6),PT11X),...
  (EXDATA(7),PT66X),(EXDATA(8),PT72X),...
  (EXDATA(9),PT73X),...
  (EXDATA(10),PT38X),(EXDATA(11),PT82X),...
  (EXDATA(12),PT13X),...

```

```

(EXDATA(13),TT14X),(EXDATA(14),TT24X),...
(EXDATA(15),TT25X),...
(EXDATA(16),TT26X),(EXDATA(17),TT27X),...
(EXDATA(18),TT29X),...
(EXDATA(19),TT32X),(EXDATA(20),TT33X),...
(EXDATA(21),TT43X),...
(EXDATA(22),TT445X),(EXDATA(23),VP162X),...
(EXDATA(24),VP170X),...
(EXDATA(25),VP295X),(EXDATA(26),VP292X),...
(EXDATA(27),WA2X),...
(EXDATA(28),WA3X),(EXDATA(29),PD3X),...
(EXDATA(30),ULTCPX),...
(EXDATA(31),HPOWRX)
constant exdata=31*0.
'File ID number'
INTEGER RFILE
CONSTANT RFILE=20

LOGICAL DATFLG
CONSTANT DATFLG = .TRUE.

IF(.NOT.REXDAT)GO TO RDEND
'OPEN EXTERNAL DATA FILE'
call Ofile

CALL RDATA(RFILE,DATFLG,EXDATA)

vp3162 = 0.01*VP162X
vp3170 = 0.01*VP170X
vp3295 = 0.01*VP295X
vp3292 = 0.01*VP292X

BFPRic = pt33x + Patm $$'pt33x in psig, BFPRic in psia'
HUPRic = pt21x + Patm $$'pt21x in psig, HUPRic in psia'
HDPRic = pt21x - PD3x $$'Delta p across heater'
MTPRic = pt11x + Patm $$'pt11x in psig, MTPRic in psia'
SCPRic = pt72x      $$'pt72x in psia, SCPRic in psia'
VSPRic = PT73x* (0.0193368) $$'Convert from mmHg to PSiA'

H UdRic = TT26x + FtoR $$'Heater inlet temperature in degR'
HUTPic = H UdRic      $$'Metal temp assumed in equilibrium'

H DdRic = TT13x + FtoR $$'Heater outlet temperature in degR'
HDTPic = H DdRic      $$'Metal temp assumed in equilibrium'
TCORic = H DdRic      $$'Heater core temp also in equilib'

MTdRic = TT32x + FtoR $$'Mixing Tee air temp in degR'
MTdrix = MTdric
MTTPic = TT14x + FtoR $$'Mixing Tee metal temp in degR'
PPTpic = MTTPic      $$' Piping volume metal temp'

SCdRic = TT445x + FtoR $$'Settling chamber air temp'

```

SCdaic = SCdRic

SCTPic = TT27x + FtoR '\$'Settling chamber metal temp'
ULTAP = ULTCPX

SCHEDULE NWDATA .AT. TIMEX
RDEND..CONTINUE

'***** General Constants for Air *****'
Constant CVair = 0.171 '\$'CV for air in [BTU/(LBM R)]'
Constant CPair = 0.240 '\$'CP for air in [BTU/(LBM R)]'
Constant R = 53.36 '\$'R for air in [ft-lbf/(LBM R)]'
Constant FtoR = 460. '\$'Conversion from degF to degR'
Constant Gamma = 1.4 '\$'CPair/CVair'
Constant JTC = 0.021 '\$'Joule-Thompson coefficient'
Constant Tref = 460. '\$'Reference Temperature'

Alpha = 2.0/Gamma \$ '1.4286'
Beta = (Gamma+1.0)/Gamma \$ '1.7143'
Prcrit = (2.0/(Gamma+1.0))**(Gamma/(Gamma-1.0)) \$ '0.5283'
Maxang = asin(1.0) '\$'Fisher valve equation constant'
Constant Patm = 14.7 '\$'Atmospheric Pressure'
Constant ATdegF = 65. '\$'Ambient Temperature degF'
ATdegR = ATdegF + FtoR '\$'Ambient Temperature degR'

'***** Constants for Heat Transfer calculations *****'
Constant XK1 = 7.666E-5, XK2 = 55004.0 '\$'Combined constants'
Constant TEXP = 0.4, QEXP = 0.8 '\$'Reynolds & Prandtl expts'

'***** Misc variables *****'
constant Tend = 0.
INTEGER LSW

'***** Calculate initial conditions *****'
'*** Battlefield IC ***'
Logical BFv1,BFv2
BFdegR = 45 + FtoR '\$'Initial Temperature'
BFdRic = BFdegR
BFmic = (BFPRic*BFvol*144)/(R*BFdegR) '\$'Initial mass'
BFenic = BFmic*CVair*(BFdegR-Tref) '\$'Initial energy'

'*** Upstream Heater volume IC ***'
HUmic = (HUPRic*HUvol*144)/(R*HUDRic) '\$'Initial mass'
HUenic = CVair*(HUDRic-Tref)*HUmic '\$'Initial energy'

'*** Downstream Heater volume IC ***'
HDmic = (HDPRic*HDvol*144)/(R*HDDRic) '\$'Initial mass'
HDenic = CVair*(HDDRic-Tref)*HDmic '\$'Initial energy'

'*** Mixing Tee volume IC ***'
MTmic = (MTPRic*MTvol*144)/(R*MTdRic) '\$'Initial mass'
MTdegR = MTdRic
MTenic = MTmic*CVair*(MTdRic-Tref) '\$'Initial energy'

```

'*** Piping volume IC ***
PPdegR = MTdRic
PPenic = 2*MTmic*CVair*(MTdRic-Tref) '$'Initial energy'

'*** Settling chamber volume IC ***
SCmic = (SCPRic*SCvol*144)/(R*SCdRic) '$'Initial mass'
SCenic = SCmic*CVair*(SCdRic-Tref) '$'Initial energy'

'*** Vacuum sphere volume IC ***
Logical Atmos '$'Discharge to atmosphere'
VSdegR = ATdegR '$'Initial Temperature'
VSmic = (VSPric*VSvol*144)/(R*VSdegR) '$'Initial mass'
VSenic = VSmic*CVair*(VSdegR-Tref) '$'Initial energy'

```

End \$ ' of Initial '

Dynamic

```

Cinterval Cint = 0.5
Constant Tstp = 100.

```

```

IF(.NOT.DATFLG)TSTP=T
Tplot = T - Tend
Termt(T .ge. Tstp)

```

Derivative

```

Algorithm Ialg = 4
Nsteps Nstp = 1
Maxterval Maxt = .01
Minterval Mint = 1.0E-08

```

```

'***** 4.2K PSI Battlefield *****
Constant BFvol = 19000. '$'Volume in ft**3'
Constant BFarea=76000. '$'Surface area in ft**2'
Constant BFCmwm=549312. '$'Specific heat*thermal mass'
Constant BFDia=12. '$'Diameter in inches'
Constant BFv1 = .true.
Constant BFv2 = .true.

```

```

'***** Battlefield Calculations *****
'Calculate Outflow = flow thru V3162 and V3292'
BFmdot = -(F3162 + WA3)
'Integrate BFmdot'
BFmas = Modint(BFmdot,BFmic,BFv1,BFv2)
'Calculate Energy'
'Heat Transfer through the Battlefield Mass not included'
BFendt = -CPair*(F3162*(TH3162-Tref) + WA3*(TH3292-Tref))
BFenrg = Modint(BFendt,0.,BFv1,BFv2) '$'Integrate BFendt'
'Temperature'
BFdegR = BFenrg/(Cvair*BFmas) + BFdRic
BFdegF = BFdegR - FtoR
'Calculate Pressure'
BFPres = BFmas*R*BFdegR/(BFvol*144.) '$'Ideal gas'
PT33 = BFPres - Patm '$'PT33 in psig"

```

'***** Valve 3162 *****'
 'Constant Cg3162 = 1190.0 '\$'Valve Cg'
 'Table look-up for v3162 Cg based on valve data p. 1-18'
 'of the Fisher catalog - includes minimum flow characteristic'
 'based on 8% equivalent opening from 0.5% to 8% opening'
 Table CGF162, 1, 14...
 /0.0,0.005,0.0051,0.08,0.1,0.2,0.3,0.4,0.5,...
 0.6,0.7,0.8,0.9,1.0,...
 0.0,0.0,65.,65.,81.8,137.,230.,376.,599.,928.,...
 1340.,1740.,2170.,2350./

Constant SF3162 = 1.0 '\$'Valve 3162 Cg scaling factor'
 Constant C13162 = 31.6 '\$'Valve C1'
 Constant w3162 = 0.667 '\$'Omega for valve linear response'
 Constant R8v162 = .10 '\$'Maximum valve rate in (% x100)/sec'
 Constant CMD162 = 0. '\$'Valve position command'
 Constant V162IC = 0. '\$'Valve position IC'

'***** V3162 Calculations *****'
 'Valve Position'
 'Err162 = w3162*(CMD162 - VP3162)'
 'V162DT = Bound(-R8v162,R8v162,Err162)'
 'VP3162 = Integ(V162DT,v162IC)'

'Determine flow direction'
 DP3162 = BFPres - HUPres '\$'(BF - Hu) pressure drop'
 SGN162 = LSW(DP3162 .GE. 0.,1,-1)
 PH3162 = RSW(DP3162 .GE. 0.,BFPres,HUPres)
 PL3162 = RSW(DP3162 .GE. 0.,HUPres,BFPres)
 TH3162 = RSW(DP3162 .GE. 0.,BFdegR,HUdegR)

'Fisher Valve calculation'
 PF3162 = 1.0 - PL3162/PH3162
 ANG162 = AMIN1(Maxang,(59.54/C13162*SQRT(PF3162)))
 CG3162 = CGF162(VP3162)*SIN(ANG162)*SGN162*SF3162
 F3162 = 4.84e-04 * CG3162 * PH3162/SQRT(TH3162)

'***** Upstream Heater volume *****'
 Constant HUvol = 17.8 '\$'Volume in ft**3'
 'Constant HUPRIC = 14.7 '\$'Initial pressure in psia'

Constant HUarea= 325. '\$'Surface area in ft**2'
 Constant HUcmwm = 2381.6 '\$'Specific Heat .117 vs. .241'

Constant HUdia= 5. '\$'Diameter in inches'

'***** Upstream Heater Calculations *****'

'Calculate mdot = (flow from 3162) - flow thru Heater orifice'
 HUmdot = F3162 - FHEATR
 'Integrate HUmdot'
 HUMAS = Integ(HUmdot,HUmic)

```

'Calculate Energy'

'Invoke Heat transfer macro'
'Macro QNRG(X,TGdegR, TMdegR, INFLO)'
QNRG('HU', HUdegR, HUTpip, amax1(F3162, FHEATR))

DT3162 = JTC*(BFpres - HUPres)
HUendt = CPair*(F3162*(TH3162-DT3162-Tref) -...
    FHEATR*(THHETR-Tref))...
    - HUQNRG

'Integrate HUendt'
HUenrg = Integ(HUendt, HUenrc)

'AIR Temperature'
HUdegR = HUenrg/(Cvair*HUMas) + Tref
TT26 = HUdegR - FtoR

'Pipe Temperature'
HUTpip = Integ(HUQNRG/HUcmwm, HUTPic)
HUpipF = HUTpip - FtoR

'Calculate Pressure'
HUPres = HUMas*R*HUdegR/(HUvol*144.) '$'Ideal gas'
PT21 = HUPres - Patm '$'PT21 in psig'

'***** Heater Flow *****
Constant CfHETR = 42.319

'***** Heater Flow Calculations *****
'Determine flow Direction'
DPHETR = HUPres - HDpres '$'(HU - HD) pressure drop'
SGNHTR = LSW(DPHETR .GE. 0., 1, -1)
PHHETR = RSW(DPHETR .GE. 0., HUPres, HDpres)
PLHETR = RSW(DPHETR .GE. 0., HDpres, HUPres)
THHETR = RSW(DPHETR .GE. 0., HUdegR, HDdegR)

FLOWSQ = CfHETR * PHHETR * (PHHETR-PLHETR)/THHETR
FHEATR = SQRT(FLOWSQ)*SGNHTR

' ***** Downstream Heater Volume *****
Constant HDvol = 42.6 '$'Volume in ft**3'
'Constant HDpric = 14.7 '$'Initial pressure in psia'

'Constant HDarea = 148.4 '$'Surface area in ft**2'
Constant HDarea = 100. '$'Effective surface area'

'Constant HDcmwm = 3676.4 '$'Specific heat*thermal mass'
'Constant HDcmwm = 1784.8'
Constant HDcmwm = 1000.

Constant HDdia = 6. '$'Diameter in inches'

```

'***** Downstream Heater Calculations *****'

```
'Calculate mdot = (flow thru heater) - flow thru 3295 and 3170'
HDmdot = FHEATR - (F3295 + F3170)
'Integrate HDmdot'
HDmas = Integ(HDmdot,HDmic)
'Calculate Energy'
'Invoke Heat transfer macro'
'Macro QNRG(X,TGdegR,TMdegR,FLO)'
```

```
QNRG('HD',HDdegR,HDTpip,amax1(FHEATR,F3295,F3170))
```

```
HDendt = CPair*(FHEATR*(THHETR-Tref)-
F3295*(TH3295-Tref)...
-F3170*(TH3170-Tref))...
- HDQNRG - M8QNRG
```

```
HDenrg = Integ(HDendt,HDnic) '$'Integrate HDendt'
```

'Air Temperature'

```
HDdegR = HDenrg/(Cvair*HDmas) + Tref
TT13 = HDdegR - FtoR
```

'Pipe Temperature'

```
HDTpip = Integ(HDQNRG/HDcmwm,HDTPic)
HDpipF = HDTpip - FtoR
```

'Calculate Pressure'

```
HDpres = HDmas*R*HDdegR/(HDvol*144.) '$'Ideal gas'
```

'***** M8 Heater *****'

```
Constant M8vol = 0.71 '$'Volume in ft**3'
```

```
Constant M8area = 342.9 '$'Surface area in ft**2'
Constant M8cmwm = 57.83 '$'Specific heat*thermal mass'
'CPMTL * WEMCOR'
Constant M8dia = 0.3675 '$'Diameter in inches'
Constant RKO = 0.3711 '$'Fixed heater resistance term'
Constant RK1 = 2.0E-05 '$'Temperature dependent resistance'
Constant MW2BTU = 947.244 '$'Conversion from MW to BTU/sec'
```

'Tap changer voltages'

```
ARRAY MLT1(3)
```

```
CONSTANT MLT1 = 164.0, 880.0, 1596.0
```

```
CONSTANT VPTAP = 24.0
```

```
Constant INLT = 1 '$'No-load tap position'
Constant KHTR=1,UZ1=0.
```

```
'Invoke M8 Heat Transfer Macro'
'Macro M8HETR(X,TGdegR,TMdegR,FLO)'
M8HETR('M8',HDdegR,TCOREr,FHEATR)
```

```

'Compute input power to heater'
NLTAP = NLT1(INLT)
VTAP = NLTAP + ULTAP * VPTAP
RHTR = RKO + (TCOREr - 615.0) * RK1
HPOWRi = RSW(HPOWRX .GT. 0.1, ...
    (VTAP * VTAP / RHTR * 1.18)*1e-06,0.)

HPOWER = KHTR*HPOWRi + UZ1

'Power in MW converted to BTUS'
QELECT = HPOWER * MW2BTU

'M8 Heater Core Temperature in degR'
TCOREr = Integ((M8QNRG+QELECT)/M8cmwm,TCORic)
TCOREf = TCOREr - FtoR

***** Valve 3170 *****
'Constant Cg3170 = 1050.0 '$'Valve Cg'
'Table look-up for v3170 Cg based on valve data p. 1-18'
'of the Fisher catalog - includes minimum flow characteristic'
'based on 8% equivalent opening from 0.5% to 8% opening'
Table CGF170, 1, 14...
/0.0,0.005,0.0051,0.08,0.1,0.2,0.3,0.4,0.5,...
    0.6,0.7,0.8,0.9,1.0,...
    0.0,0.0,156.,156.,195.,373.,530.,667.,787.,...
    889.,976.,1040.,1050.,1050./

Constant SF3170 = 1.2      '$'Valve 3170 Cg scaling factor'
Constant C13170 = 27.3     '$'Valve C1'
Constant w3170 = 0.667     '$'Omega for valve linear response'
Constant R8v170 = 0.1       '$'Maximum valve rate in (% x100)/sec'
Constant CMD170 = 0.        '$'Valve position command'
Constant V170IC = 0.        '$'Valve position IC'

***** V3170 Calculations *****
'Valve Position'
'Err170 = w3170*(CMD170 - VP3170)'
'V170DT = Bound(-R8v170,R8v170,Err170)'
'VP3170 = Integ(V170DT,v170IC)'

'Determine flow direction'
DP3170 = HDpres - Patm '$'(HD - Patm) pressure drop'
SGN170 = LSW(DP3170 .GE. 0.,1,-1)
PH3170 = RSW(DP3170 .GE. 0.,HDpres,Patm)
PL3170 = RSW(DP3170 .GE. 0.,Patm,HDpres)
TH3170 = RSW(DP3170 .GE. 0.,HDdegR,ATdegR)

'Fisher Valve calculation'
PF3170 = 1.0 - PL3170/PH3170
ANG170 = AMIN1(Maxang,(59.54/C13170*SQRT(PF3170) ) )
Cg3170 = CGF170(VP3170)*SIN(ANG170)*SGN170*SF3170
F3170 = 4.84e-04 * Cg3170 * PH3170/SQRT(TH3170)

```

'***** Valve 3295 *****'

Constant Cg3295 = 3627.0 '\$'Valve Cg - determined from Matlab'
'analysis of data'

'Table look-up for v3295 Cg based on valve data p. 1-18'
'of the Fisher catalog - includes minimum flow characteristic'
'based on 8% equivalent opening from 0.5% to 8% opening'

Table CGF295, 1, 9 ...

/0.0,0.005,0.0051,0.1,0.2,0.3,0.4,0.5,1.0,...
0.0,0.0,20.,513.,826.,1014.,1306.,1633.,2180./

' 0.0,0.0,20.,261.,326.,653.,980.,1306.,1633.,...
1960.,2286.,2613.,2940.,3627./'

Constant SF3295 = 3.0 '\$'Valve 3295 Cg scaling factor'
Constant C13295 = 20.9 '\$'Valve C1'
Constant w3295 = 0.652 '\$'Omega for valve linear response'
Constant R8v295 = 0.1 '\$'Maximum valve rate in (% x100)/sec'
Constant CMD295 = 0. '\$'Valve position command'
Constant V295IC = 0. '\$'Valve position IC'

'***** V3295 Calculations *****'

'Valve Position'
'Err295 = w3295*(CMD295 - VP3295)'
'V295DT = Bound(-R8v295,R8v295,Err295)'
'VP3295 = Integ(V295DT,v295IC)',

'USED FOR READING EXTERNAL DATA'
VP295i = RSW(VP3295 .LT. 0.005,0.,VP3295)

'Determine flow direction'
DP3295 = HDpres - MTPres '\$'(HD - MT) pressure drop'
SGN295 = LSW(DP3295 .GE. 0.,1,-1)
PH3295 = RSW(DP3295 .GE. 0.,HDpres,MTPres)
PL3295 = RSW(DP3295 .GE. 0.,MTPres,HDpres)
TH3295 = RSW(DP3295 .GE. 0.,HDdegR,MTdegR)

'Fisher Valve calculation'
PF3295 = 1.0 - PL3295/PH3295
ANG295 = AMIN1(Maxang,(59.54/C13295*SQRT(PF3295)))
Cv3295 = CGF295(vp3295)
F3295 = 4.84e-04 * Cv3295 * PH3295/SQRT(TH3295)

'***** Valve 3292 *****'

Constant Cg3292 = 3910.0 '\$'Valve Cg'
Constant C13292 = 28.9 '\$'Valve C1'
Constant w3292 = 0.261 '\$'Omega for valve linear response'
Constant R8v292 = 0.1 '\$'Maximum valve rate in (% x100)/sec'
Constant CMD292 = 0. '\$'Valve position command'
Constant V292IC = 0. '\$'Valve position IC'

'***** V3292 Calculations *****'

'Valve Position'
'Err292 = w3292*(CMD292 - VP3292)'
'V292DT = Bound(-R8v292,R8v292,Err292)'
'VP3292 = Integ(V292DT,v292IC)',

```

'USED FOR READING EXTERNAL DATA'
VP292i = RSW(VP3292 .LT. 0.005,0.,VP3292)

'Determine flow direction'
DP3292 = BFPres - MTPres $$'(BF - MT) pressure drop'
SGN292 = LSW(DP3292 .GE. 0.,1,-1)
PH3292 = RSW(DP3292 .GE. 0.,BFPres,MTPres)
PL3292 = RSW(DP3292 .GE. 0.,MTPres,BFPres)
TH3292 = RSW(DP3292 .GE. 0.,BFdegR,MTdegR)

'Fisher Valve calculation'
PWA3 = 1.0 - PL3292/PH3292
ANG292 = AMIN1(Maxang,(59.54/C13292*SQRT(PWA3) ) )
Cv3292 = Cg3292*SIN(ANG292)*SGN292
WA3 = 4.84e-04 * VP292i * Cv3292 * PH3292/SQRT(TH3292)

'***** Mixing Tee volume *****
Constant MTvol = 188.9      $$'Volume in ft**3'
'Constant MTPRic = 14.7      $$'Initial pressure in psia'

Constant MTarea = 596.8      $$'Surface area in ft**2'
'Constant MTcmwm = 2177.2    $$'Specific heat*thermal mass '
Constant MTcmwm = 4000.      $$'Specific heat*thermal mass '
Constant MTdia = 14.0        $$'Diameter in inches'
Constant MThc = 2.0e-04       $$'Fixed convective coefficient'

' ***** Mixing Tee Calculations *****
'Calculate mdot = (flow thru 3295 and 3292) - flow thru 3296'
MTmdot = (F3295 + WA3) - F3296
'Integrate MTmdot'
MTmas = Integ(MTmdot,MTmic)
'Calculate Energy'
'Invoke Heat transfer macro'
'Macro QNRG(X,TGdegR,MTdegR,INFLO)

QNRG('MT',MTdegR,MTTpip,amax1((F3295+WA3),F3296))

MTcnrg = ((TH3292-DT3292) - MTTpip)*...
          MTarea*ABS(WA3)*MThc
MThnrg = ((TH3295-DT3295) - MTTpip)*...
          MTarea*ABS(F3295)*MThc

DT3292 = JTC*(BFPres - MTPres)
DT3295 = JTC*(HDPres - MTPres)

MTendt = CPair*(F3295*(TH3295-DT3295-Tref)...
               + WA3*(TH3292-DT3292-Tref)...
               - F3296*(TH3296-Tref))...
               - MTQNRG -MTcnrg - MThnrg

MTenrg = Integ(MTendt,MTenic) $$'Integrate MTendt'

```

```

'Temperature'
MTdegR = MTenrg/(Cvair*MTmas) + Tref
TT32 = MTdegR - FtoR
'Pipe Temperature'
MTTPip = Integ(MTQNRG/MTcmwm,MTTPic)
TT14 = MTTPip - FtoR
'Calculate Pressure'
MTPres = MTmas*R*MTdegR/(MTvol*144.) '$'Ideal gas'
PT11 = MTPres - Patm '$'PT11 in psig'

'***** Piping Volume *****
'This volume represents the piping between MT and V3296'
'This volume is considered to be part of mixing tee volume'

Constant PParea = 1000.      '$'Surface area in ft**2'
Constant PPcmwm = 8000.      '$'Specific heat*thermal mass'
Constant PPdia = 14.0        '$'Diameter in inches'

PPendl = CPair*F3296*(MTdegR - PPdegR) - PPqnrg
PPenrg = Integ(PPendl,PPenlc)
PPdegR = PPenrg/(CVair * 2*MTmas) + Tref
TT999 = PPdegR - FtoR
QNRG('PP',PPdegR,PPTPip,amax1((F3295+WA3),F3296))

'Pipe Temperature'
PPTPip = Integ(PPQNRG/PPcmwm,PPTPic)
TT998 = PPTpip - FtoR

'***** Valve 3296 *****
Constant Cg3296 = 1.0      '$'Valve Cg - not used for 3296'
Constant C13296 = 1.0      '$'Valve C1 - not used for 3296'
Constant w3296 = 0.783     '$'Omega for valve linear response'
                           '$'Omega not used for 3296'
Table CGF296, 1, 2 ...
/1.1, 7.1, ...
3.53, 20.636/
Constant vp3296 = 1.1      '$'Valve 3296 setting in inches'
Cf3296 = CGF296(vp3296)

'***** V3296 Calculations *****
'Determine flow direction'
DP3296 = MTPres - SCPres '$'(MT - SC) pressure drop'
SGN296 = LSW(DP3296 .GE. 0.,1,-1)
PH3296 = RSW(DP3296 .GE. 0.,MTPres,SCPres)
PL3296 = RSW(DP3296 .GE. 0.,SCPres,MTPres)
TH3296 = RSW(DP3296 .GE. 0.,MTdegR,SCdegR)

'Orifice flow calculation'
PF3296 = BOUND(Prcrit,1.0,PL3296/PH3296)
'bottom bound is Prcrit, upper bound not restrictive'
XPR296 = PF3296**Alpha - PF3296**Beta
F3296 = 2.056*Cf3296*PH3296*SQRT(XPR296/TH3296)*SGN296

```

```

***** Settling Chamber *****
Constant SCvol = 1881.5 '$'Volume in ft**3'
'Constant SCPRic = 14.7' '$'Initial pressure in psia'

Constant SCarea = 1116.4 '$'Surface area in ft**2'
Constant SCcmwm = 4004.4 '$'Specific heat*thermal mass'
Constant SCdia = 63.0 '$'Diameter in inches'

***** Settling Chamber Calculations *****
'Calculate mdot = (flow thru 3296) - flow thru nozzle'
SCmdot = F3296 - FNOZL
'Integrate SCmdot'
SCmas = Integ(SCmdot,SCmic)
'Calculate Energy'
'Invoke Heat transfer macro'
'Macro QNRG(X,TGdegR,THdegR,INFLO)'
'Heat transfer based on INFLOW'

QNRG('SC',SCdegR,SCTPip,amax1(F3296,FNOZL))

SCendt = CPair*(F3296*(PPdegR-Tref)...
- FNOZL*(THNOZL-Tref))...
- SCQNRG

SCenrg = Integ(SCendt,SCenic) '$'Integrate SCendt'

'Temperature'
SCdegR = SCenrg/(Cvair*SCmas) + Tref
TT445 = SCdegR - FtoR
'Pipe Temperature'
SCTPip= Integ(SCQNRG/SCcmwm,SCTPic)
TT27 = SCTPip - FtoR

'Flow and Flow Energy'
SCPres = SCmas*R*SCdegR/(SCvol*144.) '$'Ideal gas'
PT72 = SCPres

***** Nozzle *****
Constant ANOZL = 14.4

***** Nozzle flow Calculations *****
'Determine flow direction'
DPNOZL = SCPres - VSPres '$'(SC - VS) pressure drop'
SGNNZL = LSW(DPNOZL .GE. 0.,1,-1)
PHNOZL = RSW(DPNOZL .GE. 0.,SCPres,VSPres)
PLNOZL = RSW(DPNOZL .GE. 0.,VSPres,SCPres)
THNOZL = RSW(DPNOZL .GE. 0.,SCdegR,VSdegR)

'Orifice flow calculation'
PFNOZL = BOUND(Prcrit,1.0,PLNOZL/PHNOZL)
'bottom bound is Prcrit, upper bound not restrictive'
XPRNZL = PFNOZL**Alpha - PFNOZL**Beta
FNOZL = 2.056*ANOZL*PHNOZL*SQRT(XPRNZL/THNOZL)*SGNNZL

```

```

'***** Vacuum Sphere *****'
'Constant VSvol = 117755.0' '$'60 ft sphere volume in ft**3'
'Constant VSvol = 523600.0' '$'100 ft sphere volume in ft**3'

Constant VSarea = 14816.0 '$'Surface area in ft**2'
Constant VScmwm = 256535.0 '$'Specific heat*thermal mass'
Constant VSdia = 72.0 '$'Diameter in inches'
Constant Atmos = .False.

'Calculate mdot = flow thru nozzle'
VSmdot = FNOZL
'Integrate VSmdot'
VSmas = Integ(VSmdot,VSmic)
'Calculate Energy'
VSendt = CVair*(FNOZL*THNOZL)
VSenrg = Integ(VSendt,VSenrc) '$'Integrate VSendt'
'Temperature'
VSdegR = VSenrg/(Cvair*VSmas) + Tref
VSdegF = VSdegR - FtoR
'Flow and Flow Energy'
VSpres = RSW(Atmos,Patm,VSmas*R*VSdegR/(VSvol*144.))
'Ideal gas'

End $ ' of Derivative '

Discrete NWDATA
  IF(.NOT.REXDAT)GO TO REXEND
    vp3162 = 0.01*VP162X
    vp3170 = 0.01*VP170X
    vp3295 = 0.01*VP295X
    vp3292 = 0.01*VP292X
    'HPOWER = HPOWRX'
    VSprsX = PT73x* (0.0193368)
    ULTAP = int(ULTCPX)

PROCEDURAL
  IF(.NOT.DATFLG) GO TO DATEND
    CALL RDATA(20,DATFLG,EXDATA)
    SCHEDULE NWDATA .AT. TIMEX
  DATEND..CONTINUE
  END$'OF PROCEDURAL'
  REXEND..CONTINUE

End$'of Discrete NWDATA'
End $ ' of Dynamic '

Terminal
tstart = tend
tend = t
End $ ' of Terminal '
End $ ' of Program '

```

```
subroutine Ofile
character*16 fname
write(*,10)
10 format(' Enter three digit data file id: \'')
read(*,*)id
fname = 'A_.DAT'
WRITE(fname(2:4),'(I3.3')ID
OPEN(UNIT=20,FILE=fname,STATUS='OLD',FORM='UNFORMATTED')
return
end

SUBROUTINE RDATA(XLUNIT,FLG,XOUT)
REAL XOUT(31),X(31)
LOGICAL FLG
INTEGER XLUNIT,TLUNIT
READ(XLUNIT,ERR=1,END=1)(X(I),I=1,31)
DO 10 I=1,31
10 XOUT(I) = X(I)
GO TO 2

1  FLG = .FALSE.
CLOSE(XLUNIT)

2  CONTINUE
RETURN
END
```



Report Documentation Page

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| 16. Abstract A simulation of the pressure and temperature responses of the 20-Inch Supersonic Wind Tunnel (SWT) is developed. The simulation models the tunnel system as a set of lumped-parameter volumes connected by flow regulating elements such as valves and nozzles. Simulated transient responses of temperature and pressure for the five boundary points of the 20-Inch Supersonic Wind Tunnel operating map are produced from their respective initial conditions, tunnel operating conditions, heater input power, and valve positions. Upon reaching steady state, a linearized model for each operating point is determined. Both simulated and actual tunnel responses are presented for comparison. | | 13. Type of Report and Period Covered Technical Memorandum | |
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